APPLICATION OF THE NAVSTAR/GLOBAL POSITIONING SYSTEM ON INSTRUMENTED RANGES

William L. Reinhart

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

APPLICATION OF THE NAVSTAR/GLOBAL
POSITIONING SYSTEM ON INSTRUMENTED RANGES

by

William L. Reinhart

March 1981

Thesis Advisor: G. A. Myers

Approved for public release, distribution unlimited

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
Application of the NAVSTAR/GLOBAL Positioning System On Instrumented Ranges

5. TYPE OF REPORT & PERIOD COVERED
Master's Thesis; March 1981

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
William L. Reinhart

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93940

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93940

12. REPORT DATE
March 1981

13. NUMBER OF PAGES
187

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
NAVSTAR; GPS; Position/Location; RMS; P/L Requirements for RTCA Experiments

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
This report treats the application of the NAVSTAR/Global Positioning System as the Position/Location System in Real Time Casualty Assessment experiments. The desirable characteristics of a position/location system are listed. A current position/location system, the Range Measuring System, is used as a comparison reference for the Global Positioning System. Operation and parameters of the Global Positioning System are presented. A description and

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

the results of a five day demonstration conducted on an instrumented range using a Global Positioning System prototype receiver are given. It is concluded that the Global Positioning System has some important advantages and that more study and further tests are needed to determine the full extent of its potential.

Application of the NAVSTAR/GLOBAL Positioning System On Instrumented Ranges

William L. Reinhart
Captain, Unites States Army
B.S.E.E., United States Military Academy, 1974

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
March 1981

ABSTRACT

This report treats the application of the NAVSTAR/Global Positioning System as the Position/Location System in Real Time Casualty Assessment experiments. The desirable characteristics of a position/location system are listed. A current position/location system, the Range Measuring System, is used as a comparison reference for the Global Positioning System. Operation and parameters of the Global Positioning System are presented. A description and the results of a five day demonstration conducted on an instrumented range using a Global Positioning System prototype receiver are given. It is concluded that the Global Positioning System has some important advantages and that more study and further tests are needed to determine the full extent of its potential.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

ACS	Attitude Control Subsystem
AFC	Automatic Frequency Control
AGC	Automatic Gain Control
AIS	Airborne Instrumentation Subsystem
AODC	Age Of Data Word (Clock)
AODE	Age Of Data Word (Ephemeris)
BER	Bit Error Rate
BPS	Bits-per-Second
C/A	Coarse/Acquisition or Clear/Access
CDEC	Combat Developments Experimentation Command
CDL	Computer Data Link
C/N_o	Carrier To Noise Ratio
CS	Computational Subsystem
DDTE	Director of Defense Test and Evaluation
DLL	Delay Lock Loop
DMA	Defense Mapping Agency
DMD	Digital Message Device
DSARC	Defense Systems Acquisitions Review Council
ECEF	Earth Centered, Earth Fixed
EIRP	Effective Isotropic Radiated Power
EMI	Electromagnetic Interference
EPS	Electrical Power Subsystem
FAA	Federal Aviation Administration
FHL	Fort Hunter Liggett

FYIP	Five Year Instrumentation Program
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
HOW	Handover Word
IMP	Instrumentation Master Plan
IMU	Inertial Measurement Unit
I/O	Input/Output
IROC	Instrumentation Required Operational Capabilities
kHz	Kilohertz
kBPS	Kilo Bits Per Second
LED	Light Emitting Diode
LPF	Low Pass Filter
MBPS	Mega Bits Per Second
MCS	Master Control Station or Multicomputer System
MHz	Megahertz
MMCS	Mobile Master Control Station
MS	Monitor Station
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NRL	Naval Research Laboratory
NSWC	Naval Surface Weapons Center
NTS	Navigation Technology Satellite
ONS	Operational Navigation Satellite
OTP	Outline Test Plan
P	Precise
PCM-AM	Pulse Code Modulation-Amplitude Modulation

PDOP	Position Dilution of Precision
P_k	Kill Probability
PL	Position/Location
PLL	Phase Lock Loop
PRN	Pseudorandom Noise
PSD	Pilot Steering Display
RF	Radio Frequency
RH	Righthand
RMS	Range Measurement (Multilateration) System
RSS	Root Sum Squared
RTCA	Real Time Casualty Assessment
RTS	Remote Tracking Station
SAMSO	Space and Missile Systems Organization
SCF	Satellite Control Facility
SGLS	Space Ground Link System
SOH	State of Health
SNR	Signal to Noise Ratio
TCS	Tracking and Communication Subsystem or Thermal Control Subsystem
TDOP	Time Dilution of Precision
TLM	Telemetry
T/R	Transmit/Receive
TT&C	Telemetry/Tracking and Control
UERE	User Equivalent Range Error
ULS	Upload Station
USDRE	Under Secretary of Defense Research and Engineering
VCO	Voltage Controlled Oscillator

I. INTRODUCTION

This research concerns evaluation of a precise position/location system suitable for use in real-time casualty assessment (RTCA) experiments on instrumented ranges. In RTCA experiments opposing fire between two sides is simulated in a battlefield environment. The instrumentation objectives are to determine who is firing at whom, simulate each engagement mathematically and provide the opposing players with realistic engagement results. Current RTCA systems use eye-safe lasers which are boresighted on direct fire weapons and sensors mounted on targets. When the laser is fired, weapon fire cueing effects are created. If any target sensors are activitated, a central computer facility is automatically notified. The computer facility assesses the conditions that determine kill probability, P_k. Conditions include weapon type, ammunition, target type, range, and position/location. The computer then notifies the targets of near misses or kills and provides feedback to the firer. This sequence of events occurs each time a weapon is fired and in as near real time as possible.

The single most important factor used by the computer in determining kill probabilities is the position/location (PL) data on each player. For this reason a great deal of time and expense has gone into designing a position/location system suitable for use in RTCA experiments. Candidate systems

for use with RTCA experiments should provide accurate position/location (PL) data on a player in reference to any other player. This PL data should be accurate to five meters or better in three dimensions, x, y and z, in a relative or absolute coordinate grid system. The PL data must be continuous and as near real time as possible for all players. This permits range personnel to monitor and direct experiments. It also enhances the realism of the simulated battlefield by providing rapid player feedback. The PL system must accomodate a wide variety of player types. It must be small and light enough to be carried by infantry personnel while being durable and rugged enough for track vehicles. It will also be required to provide accurate PL data on high performance fixed and rotary wing aircraft. A very desirable characteristic of a potential system is its ability to be exportable. Exportability of a system means providing PL data for an experiment anywhere in the world without equipment transportation problems or lengthy equipment set up time. A desirable feature is a player capacity sufficient to perform experiments involving a dismounted Battalion Task Force against a dismounted Company team of approximately 375 players. The PL system must be flexible. It should have the flexibility to permit concurrent experiments. The determination of PL data from one trial or experiment should not limit or interfere with the PL determination in another experiment. Above all, the PL data must be reliable. Unreliable data invalidates time consuming trials which only extends experiments. This

ties up personnel and equipment at tremendous additional expense. To be reliable it must be all-weather, terrain independent (multipath effect) and reject the effects of electromagnetic interference (EMI) caused by other equipment utilized in the experiment. This list of desirable characteristics is not all inclusive but it does point out the more demanding requirements.

A. OBJECTIVE

The objective of this research is to investigate the application of the NAVSTAR/Global Positioning System (GPS) in RTCA experiments on instrumented ranges. GPS is a satellite based navigation system currently undergoing full scale engineering development testing by the Department of Defense at Yuma Proving Ground, Arizona. When fully deployed, GPS has the potential of providing continuous highly accurate three dimensional position, velocity and time to an infinite number of suitably equipped users anywhere in the world. The report will investigate the position/location requirements of a RTCA system and look at the potential of the NAVSTAR/Global Positioning System in meeting those requirements.

B. APPROACH

The approach used to investigate the possible use of the NAVSTAR/Global Positioning System on an instrumented range was first to understand the requirements of a position/location system in RTCA experiments. An instrumented range

was chosen where current RTCA experiments are being conducted. The range is located at Fort Hunter Liggett, California, 90 miles south of Monterey. The United States Army Combat Developments Experimentation Command, with its headquarters at Fort Ord, California has conducted extensive tests using RTCA to evaluate tactics development and weapons systems requirements since 1970. The position/location system used to support the RTCA experiments is known as the Range Measuring System (RMS).

A thorough study of RTCA experiments was conducted with emphasis on the requirements of the position/location system. The study included reports on past and present experiments as well as the outline test plans (OTP) of future experiments. These reports indicated the important parameters that were measured such as position/location, velocity and acceleration. They also indicated the current accuracy with which these parameters can be measured.

In addition to the experiments, long range planning documents produced by CDEC were analyzed. These planning documents are used by CDEC personnel to enhance the performance of current instrumentation systems and extend the present system's capabilities to meet near term experimentation needs. The documents included the Instrumentation Required Operational Capabilities (IROC), Instrumentation Master Plan (IMP) and the Five Year Instrumentation Program (FYIP). They highlight the current and future requirements of instrumentation systems which support RTCA experiments.

The current position/location system used at Fort Hunter Liggett was used to evaluate the NAVSTAR/Global Position System. A study was conducted on the Range Measuring System (RMS) to determine its operational performance. Recent experiments and specific studies conducted to determine RMS accuracies were reviewed. The system's strong and weak points as well as error sources have been identified to more fully and fairly use it in a comparison with GPS. A detailed description of the RMS system and its characteristics are found in Appendix A.

A thorough study of the GPS program was performed. Presented in this report as Appendix B is a general description of the system, a detailed description of how the system works, and expected performance. Results from Phase I testing were used to characterize its performance and identify error sources.

To fully satisfy the objective of investigating the application of the Global Positioning System on instrumented ranges, a demonstration of GPS was conducted at Fort Hunter Liggett. The demonstration was conducted with a Phase I prototype GPS receiver. The goal of the demonstration was twofold. First, it was to gain familiarity with the manpack receiver equipment. The second goal of the demonstration was to qualitatively evaluate the performance of the receiver at Fort Hunter Liggett. This would subject the receiver to the

same terrain conditions as an actual experiment and permit a more valid comparison between GPS and RMS. Data was recorded for each of the five days of the demonstration and used in post-demonstration analysis to verify expected accuracies. A different scenario for each of the five days of the demonstration was used in an attempt to identify specific error sources. The error sources of interest included terrain induced multipath and signal attenuation due to foliage and vegetation. A detailed account of the demonstration, data obtained and conclusions drawn is found in Part IV of this paper.

II. RANGE MEASURING SYSTEM

A. DEFINITION OF RANGE MEASURING SYSTEM

The majority of the experiments conducted at Fort Hunter Liggett by the Combat Developments Experimentation Command (CDEC) are known as Real Time Casualty Assessment (RTCA) experiments. The field experiments evaluate selected aspects of organizational, operational and material concepts within the framework of performance of combat tasks under simulated and controlled battlefield conditions. Therefore, there exists a basic requirement in all experiments conducted by CDEC to establish the time-space relationship among all participating players during experimental trials.

The Range Measuring System (RMS) was conceived as a means of rapidly determining continuously the relative position of men, vehicle (both wheel and track) and aircraft (rotary and fixed wing) in mock battle.

B. REQUIRED CAPABILITIES

The success of RTCA is highly dependent upon how well the following things are done or known. First is the weapon-target pairing which is done via a laser sensor pairing system. Next is the player position/location (PL). This information is obtained by a range multilateration technique. Finally, the RTCA system must combine the laser-sensor pairing with player

position/location information and communicate it over a two-way telemetry link to a central processing facility for the purposes of casualty assessment and player feedback. Time and position/location, when taken together with pertinent events, form the essential basis of experimental data. For most of the experiments conducted by CDEC, position/location information is a fundamental and sometimes primary element in the experimental data.

Position/location is accomplished by three basic groups of devices: sensor equipment in the field, a data link and a central computing facility. The instrumentation system in use at Fort Hunter Liggett to accomplish these goals is RMS. A brief history of RMS is helpful in understanding the current position/location system in use at Fort Hunter Liggett.

C. BRIEF HISTORY OF RMS AT FORT HUNTER LIGGETT

In the mid 1960s the U.S. Army's Combat Developments Experimentation Command (CDEC) contracted with Stanford Research Institute to perform a study of PL techniques and recommend those of greatest promise for future development. This study was based on theoretical analysis, field measurements of propagation anomalies, signal margins required and multipath effects and vulnerability. The study forecasted the technology required to develop an operational system. A major portion of the study was devoted to evaluating and comparing two principal approaches to such a system,

continuous wave and pulse techniques. The study concluded that the pulse system was the inherently superior approach. The Electronics Division of General Dynamics developed a position/location and data collection system that reflected the study guidelines.

The original PL system developed by General Dynamics was designed and built for CDEC's field laboratory at Fort Hunter Liggett, California and was called the Range Measuring System (RMS). The system underwent acceptance testing in 1969 at CDEC's field laboratory. Successful acceptance trials and subsequent use of RMS at Fort Hunter Liggett by CDEC over the last ten years have validated the conclusion of the study that a pulse-range system can provide accurate and reliable PL information for operational testing and evaluation of ground and air players.

D. GENERAL DESCRIPTION OF RMS AT FORT HUNTER LIGGETT

The current position/location system at Fort Hunter Liggett has been reliable and provided accurate results over the last ten years and many experiments. Many modifications in both hardware and software have been made to keep pace with rapidly changing technology. These modifications have permitted RMS to accomodate much larger and more complex experiments than initially envisioned. A recent example is the Tactical Aircraft Survivability Evaluation (TASVAL) experiment conducted June 1978 to September 1979. In this

experiment, the RMS system was operated at near maximum capacity. It was required to track in excess of 100 players in an area covering over 200 km^2 [Ref. 1]. The players included personnel, vehicle (wheel and track) and aircraft (fixed and rotary wing). Position accuracy in the x and y plane was needed to 5 meters or better while 10-50 meters in altitude information was needed. In addition to PL information, velocity information was required on each player. All of this data was needed in real-time.

Although RMS was operated at near capacity for TASVAL, it was able to satisfactorily perform most of its functions at the required accuracies. Future experiments will undoubtedly require the PL system used by CDEC to accomodate larger and more complex experiments. Based on post-experiment analysis of previous experiments and projected experiments, CDEC anticipates that the capabilities/accuracies listed in Table 1 will be required of the position/location system used for future experiments. In addition to the requirements/capabilities for future experiments, Table 1 lists the current capabilities and deficiencies that exist with RMS [Ref. 2].

RMS has two critical roles which it must perform reliably and accurately if the data from an experiment is to be useful. It is a combination PL and telemetry system. The position/location function is performed by a multilateration process.

TABLE 1 REQUIREMENTS/CAPABILITIES FOR PLAYER POSITION/MOTION [Ref. 2]

REQUIREMENT	SPECIFICATION	CURRENT CAPABILITY	DEFICIENCIES
Positions for Management & Control	±50m of true x,y. ±50m z (aircraft only) Data rate proportional to target speed.	RMS and VIDS meet.	
	Extended aircraft position.	Provided by test proponent.	
Range for RTCA	±5m to 50m. ±10% between 50m and 1 km. ±100m beyond 1 km.	RMS meets in clean environment.	Degraded by trees or buildings. Tests required.
Position for RTCA (x,y components)	±10m(Arty/bombs).		
Motion for RTCA (x,y components)	±10° direction (tank). ±5° direction (a/c). ±5m/sec speed (a/c). ±3m displacement(a/c). ±2m/sec speed(tank). ±1m displacement(tank).	Marginal capability with RMS.	Finely tuned RMS array required.
Altitude Component for RTCA	±20m position. ±5° direction. ±3m displacement		Airborne A required.
Precision Position/ Motion	±.5m of true x,y. ±.5m/sec of true velocity. ±.5m/sec^2 of true acceleration	Limited. (Aerial photography)	Limited to single target & small area. Labor intensive. Not available for RTCA.

Multilateration consists of measuring the ranges to a player from several known locations. These ranges, known as slant ranges, are then applied to a computer where a computation algorithm smooths the range data and computes the location of the player.

The PL and telemetry portion of RMS consist of three major components: a master control station, many interrogators and player mounted transponder units. Fig. 1 depicts the typical layout of these components for a recent experiment.

The master control station, MMCS or C-station, is a computer which controls the system by addressing specified interrogators and requesting a range reading on a specified palyer which is carrying a transponder. The range is computed by the interrogator (A-station) by measuring the elapsed time for a pulse to traverse from the A-station to the transponder (B unit) and back again. The A-station then responds to the MMCS with a 17 bit range message. The PL data is available for real time display using the system's display subsystem for immediate analysis. All position data is recorded for post trial analysis. Additional relay interrogator stations (D-station) which relay signals between the MMCC and A-station can be used to extend the range of RMS to a maximum of 64 km [Ref. 3].

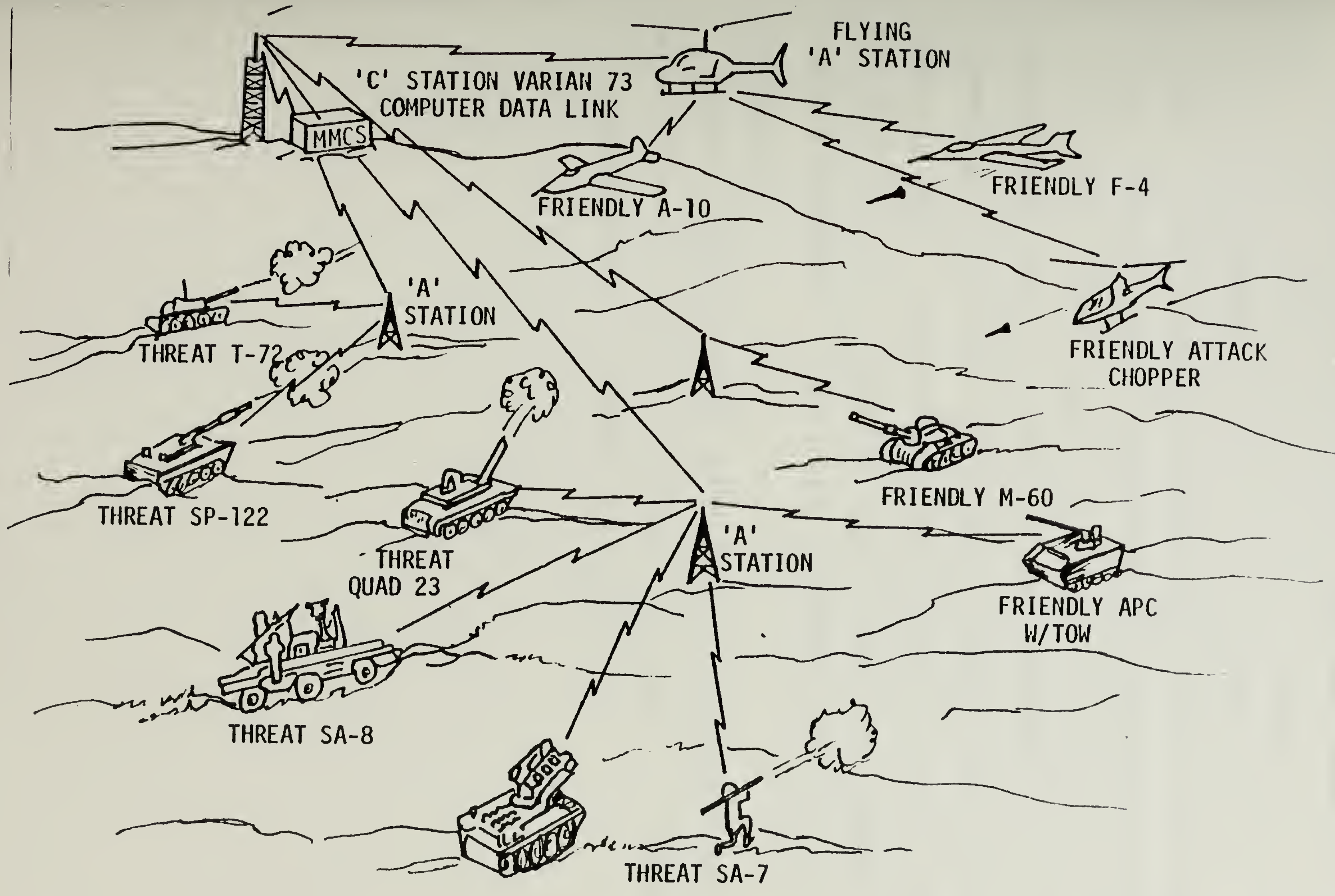

Fig. 1 Typical Layout of RMS Components

In addition to its PL function, RMS also serves as a telemetry system. It has the capability of sending to or receiving from a particular B unit, a 42 bit digital message. This message is used to transmit events from the test participants to the C-station or send commands to the units being tracked.

A recently added capability to RMS is its ability to gather attitude information on aircraft. By the addition of an instrument pod, three axis attitude, air speed, angle of attack, side slip angle, accelerations, and velocities can be tracked. The instrument pod carried by a player aircraft contains a B-unit transponder, gyro package, microprocessor and air speed transducers.

Table 2 summarized the characteristics of the PL and telemetry subsystem of RMS. A technical description of RMS and its capabilities is included in Appendix A.

TABLE 2 CHARACTERISTICS OF THE PL AND TELEMETRY SUBSYSTEM OF RMS [Ref. 4]

Modes of Operation	1. RNG (Ranging) 2. SCM (Short communication Mag) 3. EAB (Extended Communication A-to B) 4. EBA (Extended Communication B-to A)
Operating Frequency	918 MHz
Type of Modulation	Pulse: Range pulses - pulsed carrier Command and MSG pulses - four subcarrier channels
Data Transmission Rate	200 kbits per second 100 kbits per second per channel
Method of Interrogation for Field Stations	Discrete Addressing B-units 10 bits (1023 addresses) A-stations 7 bits (127 addresses) D-stations 3 bits (7 addresses)
Typical Transmission Range (Line-of-Sight)	C to A 36 km A to B 64 km
Transmitter power	40.8 dBm peak min (12 watts)
Transmission Duty Cycle (Max)	C station: 30% D station: 30% A station: 8.5% B unit: 1.0%

III. GLOBAL POSITIONING SYSTEM

A. GENERAL DESCRIPTION OF SYSTEM

The NAVSTAR/Global Positioning System (GPS) is a continuous, world-wide, all weather position system that provides precise position and velocity data along the three axes of a Cartesian earth centered, earth fixed (ECEF) coordinated system. GPS utilizes a passive ranging technique to provide real-time, continuous navigation information to an unlimited number of authorized users.

The system is composed of three major segments: the space segment, control segment and user segment. The space segment consists of many satellites in 12 hour orbits at an approximate altitude of 20,183 km. The satellites transmit two L-band signals which are modulated with navigation data. The navigation data is provided by the ground control segment. In addition to providing the navigation data, the ground control segment tracks and provides the command and control for the space segment. The user segment is composed of the necessary receiver equipment used to detect the two L-band navigation signals, and a navigation computer is used to calculate the user's position.

B. EARLY HISTORY

The idea of navigation by satellite is not new. The National Aeronautics and Space Administration (NASA) did the first work in navigation by satellite in the early 1960s but subsequently withdrew when the Department of Defense began funding work done by the Air Force and the Navy. The Air Force work done in navigation by satellite was known as the 621B program. It consisted primarily of studies of different navigation techniques conducted by several major educational institutions. The Navy's early work in navigation by satellite was conducted by the Naval Research Lab (NRL). It was from this work that the TIMATION series of satellites was developed. In 1967 the Navy demonstrated for the first time that navigation by a time synchronized satellite was possible using ranges and doppler measurements from a single satellite.

In 1973 the Secretary of Defense directed the merger of the Navy's TIMATION program with the Air Force 621B program. The 1973 memo issued by the Deputy Secretary of Defense designated the Air Force as the executive service in a joint service effort to develop a satellite based passive ranging system to meet contemporary military navigation requirements. This was the birth of the NAVSTAR/Global Positioning System. It was to be built on the technological achievements of the predecessor Air Force and Navy programs and also incorporate the PL requirements of the Army and the Defense Mapping Agency (DMA).

The performance objectives for the new satellite navigation system were very demanding. It must provide high accuracy, 10-30 meters rms position error. It must provide real-time navigation for high dynamic users. Also, it must provide world-wide operation while being tolerant to non-intentional or intentional inferference. Finally, the user equipment should not be required to have a synchronous clock and an initial fix should be obtained in a matter of minutes, not hours.

The Defense Systems Acquisitions Review Council (DSARC), which was held in December 1973, approved the NAVSTAR/GPS concept and gave subsequent approval for the first, the Concept Validation Phase, of three system acquisition phases to begin. The final satellite in the TIMATION series was launched in July 1974, after the merger with the Air Force program. The spacecraft was renamed Navigation Technology Satellite 1 (NTS-1) and became the first of a series of navigation satellites to be launched in support of the NAVSTAR/GPS program. NTS-2 was the first satellite designed and built under the sponsorship of the NAVSTAR/GPS program. It was placed at the nominal altitude selected for operational NAVSTAR/GPS satellites. It carried a cesium time standard and the navigation subsystem planned for the operational GPS system.

The Joint Program Office for GPS located at the Space and Missile Systems Organization (SAMSO), Los Angeles Air Force Station, is assisted by the Aerospace Corporation and acts as

the overall GPS program contractor. In addition to the major services from Department of Defense, the Federal Aviation Administration (FAA), the maritime service and NATO have become active participants in the NAVSTAR/GPS program.

C. PHASES I, II AND III

The first phase of the GPS acquisition cycle, the Concept Validation Phase was successfully completed in June 1979. The objective of Phase I was to evaluate the performance of the user receiving equipment and the control segment. To support Phase I testing, six satellites were launched to provide a pilot space configuration. The orbits were such that a maximum test period was provided over the Army's Yuma Proving Ground, Arizona which was the primary test area for the GPS evaluation. Some of the results from the Phase I testing will be covered later in this report.

Phase II, Full Scale Engineering Development, began in 1979 and is scheduled to last until 1983. There are three primary objectives for Phase II. First, operational spacecraft will be developed and a transition will be made to shuttle launches. Second, operational ground and control systems will be further developed and installed. Finally, two contractors will develop about 50 user equipment sets for evaluation on nine host vehicles. The majority of Phase II testing is also scheduled for Yuma Proving Ground. The final phase of NAVSTAR/GPS development is the production and full

operational deployment. It is scheduled to begin in 1983, and present plans indicate that the system will be totally operational and providing continuous, world-wide coverage, three dimensional position and velocity information for authorized users by 1987.

D. PRINCIPLES OF SATELLITE NAVIGATION

The NAVSTAR/GPS uses a passive ranging technique where the user accurately measures the slant range between himself and the satellite. The measurement of this distance is obtained by measuring the transit times of satellite generated signals. Because the system is passive, the measurements are meaningful only if the times at which they are transmitted and received are precisely known. To be precisely known, the user would be required to carry a clock synchronized with the satellite's clock which violates one of the performance objectives of the NAVSTAR/GPS program. To avoid this dilemma, the user must correct the apparent transmit time with information supplied to him or solved for by him.

Fig. 2 shows the GPS satellite constellation required for a user to determine his position in three dimensions. The coordinate system used in the GPS position solution is a Cartesian earth-centered, earth fixed system with the x axis in the true equatorial plane in the direction of the Greenwich meridian. The z axis is along the true earth spin axis (positive in the northern hemisphere) and the y axis completes

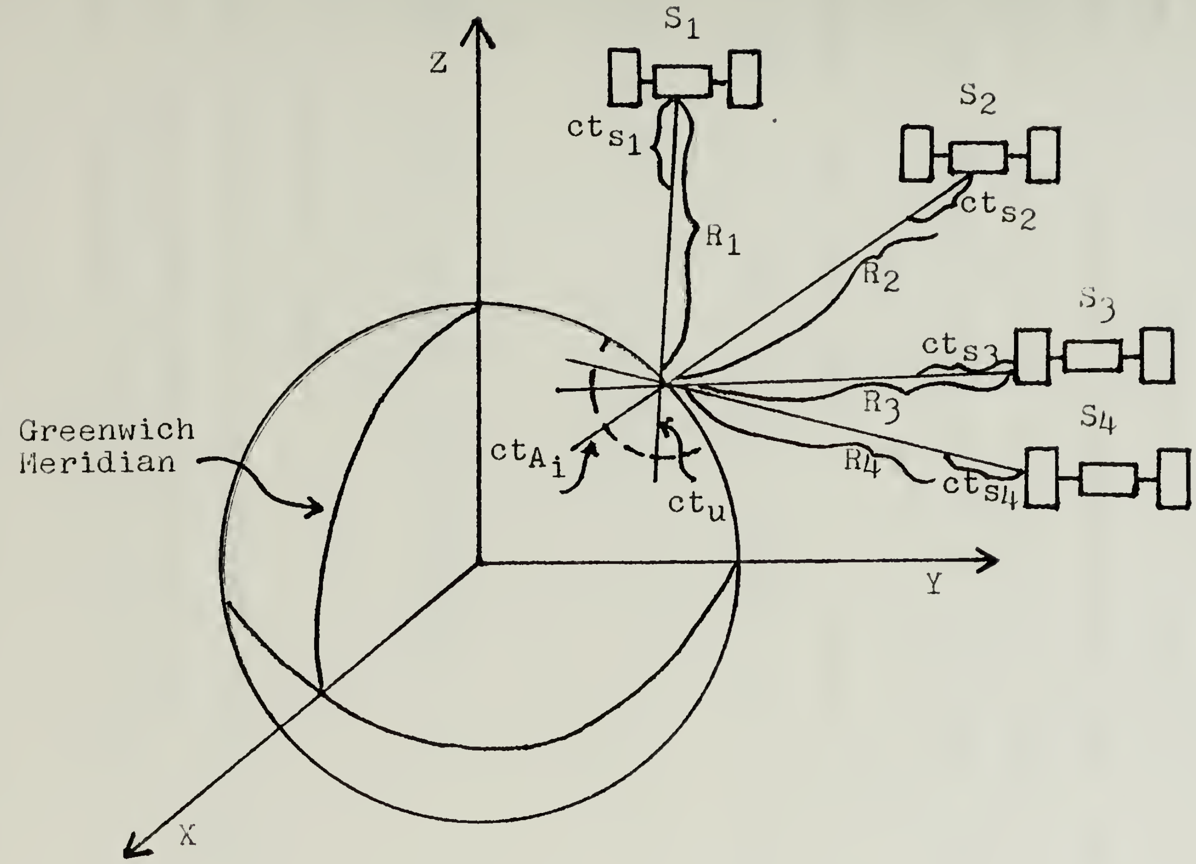

Fig. 2 Relationship of Times Between Satellites and Users and Their Respective Range

the righthand system. The GPS user measures the apparent transit time by measuring the phase shift of identical pseudo-random noise (PRN) codes that are generated in both the satellite and the user's receiver, each synchronized with its own clock. The receiver code is shifted until maximum correlation is achieved between the two codes. The time magnitude of the shift is the receiver's measure of transit time. This quantity when scaled by the radio signal propagation velocity represents the true slant range plus propagation delays and time biases. It is referred to as the pseudo-range, $P\bar{R}_i$. The equation for pseudo-range is the following:

$$P\bar{R}_i = R_i + c\Delta t_{Ai} + c(\Delta t_u - \Delta t_{si}) \qquad i = 1,2,\ldots,4$$

where

$P\bar{R}_i$ = pseudo-range to satellite (s_i)

R_i = true slant range

c = speed of light

Δt_{si} = satellite (s_i) clock offset from GPS time

Δt_u = user clock offset from GPS time

Δt_{Ai} = propagation delays and other errors

In addition to the pseudo-range, the user also receives information from demodulation of the satellite signal. Included in the demodulated data is precise three dimensional satellite position information, satellite clock correction

coefficients and atmospheric delay parameters. With this information from each satellite and the pseudo-range to each satellite the user can formulate four equations (one for each satellite, s_i) which contains four unknowns, user position in ECEF coordinates, x, y, z and the user clock offset from GPS time, Δt_o. The equations are of the following form:

$$\bar{PR}_i = [(x_{s_i}-x_u)^2 + (Y_{s_i}-Y_u)^2 + (Z_{s_i}-Z_u)^2]^{1/2}$$

$$+ c\Delta t_A + c(\Delta t_u - t_{s_i})$$

The user can then solve for his position by the simultaneous solution of four equations with four unknowns.

The system requires the precise synchronization of the satellite clocks with GPS time. This is accomplished by use of atomic frequency standards in each satellite and the use of clock correction coefficients provided to the user. Notice that if users could maintain a precision clock synchronized with GPS time, navigation could be accomplished with only three satellites. The fourth satellite permits the user to estimate his clock offset from true GPS time.

E. THREE SEGMENT SYSTEM

The NAVSTAR/GPS consists of three major segments: space, control and user. The space segment consists of 18 or 24 satellites in 12 hour orbits at an altitude of 20,183 km.

This allows for four or more satellites to always be visible (greater than 5° above the horizon). All satellites transmit two L-band signals (L-1575.42 MHz and L-1227.6 MHz) which permit ionospheric delay corrections. A spread spectrum modulation technique is used to provide the precise timing marks, separate the various satellite signals and obtain processing advantage against multipath and jamming signals.

The data modulated on the two L-band signals is provided by the ground control segment. It includes precise satellite ephemeris information, satellite clock correction coefficients and atmospheric parameters for one channel users. The ground control segment continuously gathers information on the satellites by its tracking network.

Fig. 3 illustrates the interrelationship among the components of the space segment, control segment and the user segment. The user segment is the third segment of the system and consists of the necessary equipment to receive the two L-band navigation signals. With data demodulated from these signals, the user can determine his position and velocity. A more detailed description of the three segments and their function is found in Appendix B.

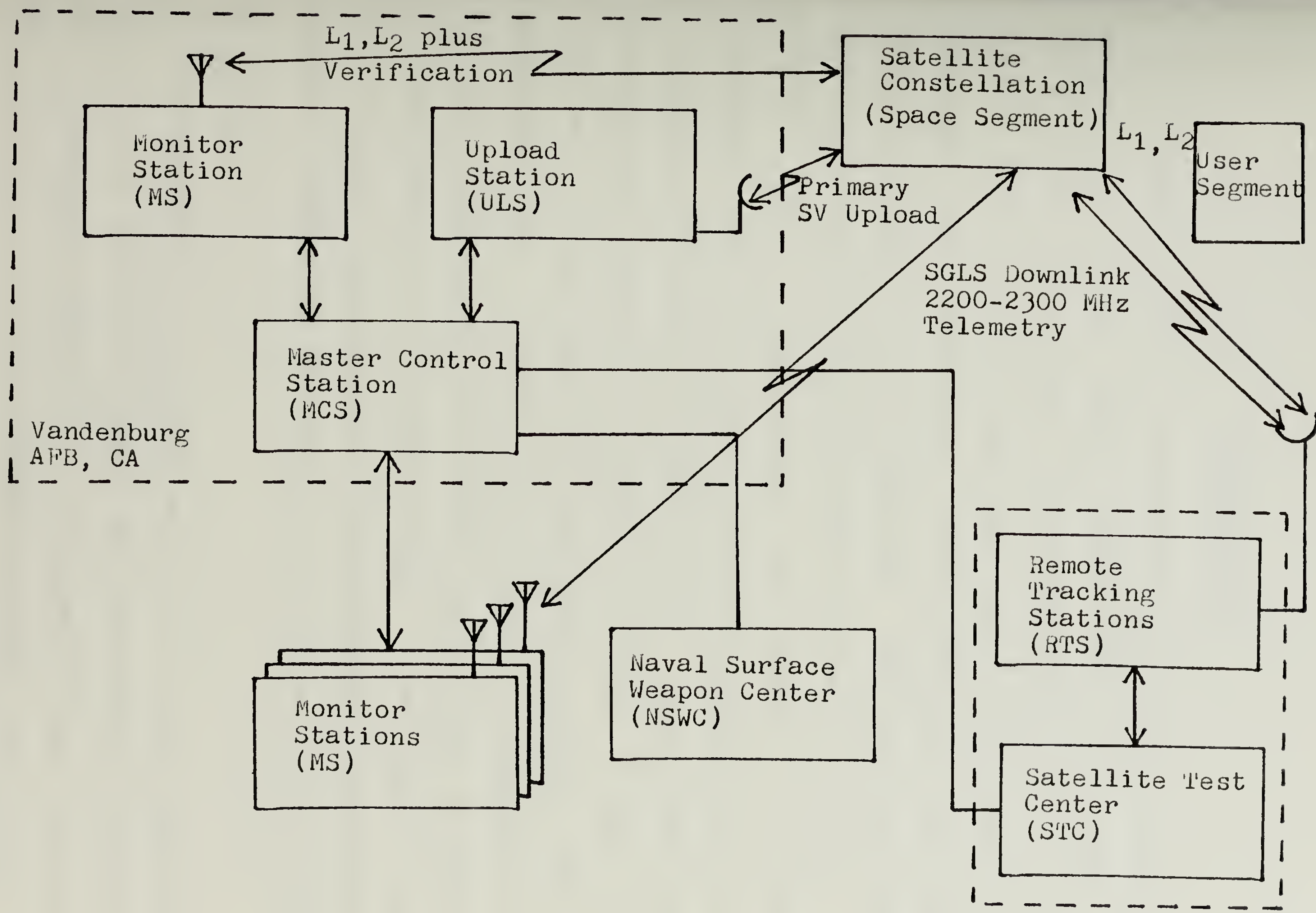

Fig. 3 System Configuration

IV. DEMONSTRATION

A demonstration of the NAVSTAR/Global Positioning System was conducted at Fort Hunter Liggett from 13-17 October 1980. The prototype GPS receiver was operated under extremes of terrain and vegetation conditions. Most of the terrain and vegetation was characteristic of areas where past and possible future experiments will be conducted. The two major areas used in the demonstration were the Nacimiento and Upper Milpitas Valleys. Both offered a good variety of terrain. Vegetation varied from sparse in the Nacimiento Valley to very heavy in the Upper Milpitas Valley. First order survey points, which are used in A station placement in RMS, provided very accurate known reference points against which to compare GPS data. The data was then used to determine if any serious degradation of GPS accuracy occurred due to the specific environment of Fort Hunter Liggett. Conclusions regarding the strong and weak points of utilizing GPS on instrumented ranges is covered in the Conclusions Section of this chapter.

A. PURPOSE

The purpose of the demonstration was to gain familiarity with the GPS receiver equipment and qualitatively evaluate its performance under actual instrumented range conditions. The familiarity with the equipment included start-up and

operation of the equipment. This occurred by actual receiver operation and through the assistance of a contractor technician who maintained the receiver equipment throughout the demonstration. The evaluation of the receiver's performance included subjecting it to similar terrain and environmental conditions as those found in actual experiments and requiring the receiver to operate in rugged terrain and thick vegetation. This was an attempt to induce multipath and signal attenuation which are thought to be potential problems with use of GPS at Fort Hunter Liggett.

B. PERFORMANCE OBJECTIVE

The performance criteria for the demonstration was divided into two areas. The first performance criteria was whether the receiver performed as indicated by the manufacturer. Selected examples of this type of performance criteria are shown in Table 3 below. These criteria were selected because of their potential impact on the quality of data and as an indication of efficient of GPS in RTCA experiments.

Table 3 Selected Receiver Characteristics

PARAMETER	VALUE
Equipment Stabilization Period	13.5 mins
Signal Source Elevation	10° above horizon
Time to First Fix	4 mins
Time Required to Initialize Receiver (Cold State-Up)(Collect Almanac)	12.5 mins
Navigation, Static (CEP)	15 meters
Navigation Solution Update(MVUE)	6 secs
I/O Capability	Keyborad, Radio Link, Pilot Steering Display

The second area of performance criteria was a subjective evaluation of the GPS system's ability to give precise position/location information when the receiver operates in various terrain and vegetation conditions. A qualitative approach was used in this area because of the short duration of the demonstration. The five days permitted only a limited amount of data to be accumulated. Although GPS is compared with the current position/location system in use, only qualitative conclusions could be drawn from the data. This is true primarily because of the large number of error sources which affect GPS position accuracy and which were not controllable throughout the demonstration. These error sources are described in detail in Chapter III.

C. EQUIPMENT

The GPS prototype receiver used in the demonstration was the Texas Instrument Manpack/Vehicular User Equipment (MVUE). It is a single-channel, microprocessor-controlled receiver capable of acquiring and processing the two-frequency signals of the GPS satellites. It was designed to be battery operated and man-transportable or vehicle mounted and operated from vehicle power.

The MVUE performs four primary functions: (1) It selects and acquires the signals from the visible GPS satellites. (2) It processes these signals and calculates an estimate of the MVUE's position and time. (3) It provides an interface

with the user through I/O devices. This interface is provided so that the MVUE can provide data to the user and accept commands and information from the user. (4) It operates in the manpack configuration with battery power or while vehicular mounted and operating off vehicle power. In proper operation, the MVUE must be able to perform all four functions.

The MVUE can be operated in eight different modes listed in Table 4.

Table 4 Functional Modes of the MVUE

1.	Off
2.	Cold Start
3.	Operate
4.	Almanac Collect
5.	Stand-By
6.	Warm Start
7.	Software Restart
8.	Built-in-Test

The cold start mode of operation is encountered when the MVUE is first turned on. The set required a 13.5 minute equipment stabilization period during which time no other actions can be performed. Once the master oscillator has stabilized, power is applied to all components and the processor memory is zeroed. A self-test is automatically conducted to determine any faults. If the self-test is successful, the operator is notified and can begin initializing the MVUE for operation. Unsuccessful completion of the self-test requires the user to correct the indicated fault prior to set initialization. The

minimum information the user must provide the MVUE to initialize is the user's position and time. The user may also specify which satellites the set is to acquire or permit the MVUE to automatically acquire those available according to a satellite select algorithm.

Once the MVUE has been initialized, it begins to sequentially acquire the satellites and recover their data. After the four satellites have been acquired and a complete almanac has been received, the MVUE can compute the user's position and time.

The other modes of operation are variations on the cold-start mode usually not requiring all of the above steps to be capable of calculating user's position. For example in the warm-start mode, the receiver has already been initialized and has collected a complete almanac. The receiver needs only to acquire the satellites to calculate a user's position and time. The stand-by mode usually precedes the warm-start mode and is used to conserve battery power by providing power to the master oscillator and other critical components. The operate mode is the usual mode of operation of the MVUE. Unless the user requires a PL determination, the MVUE will automatically display the current user's position once per minute. The built-in test mode is an additional fault detection mode and was not used in the demonstration at Fort Hunter Liggett.

The MVUE consists of five components. They are the receiver/processor, the control display unit (CDU), the vehicle installation kit (VIK), the MVUE antenna and the battery pack. These components are shown in Figs. 4, 5 and 6. The vehicle configuration and manpack unit are shown in Figs. 7 and 8 respectively.

The MVUE receiver/processor contains all of the hardware and software necessary to acquire, track and demodulate the satellite signals as well as perform all of the required computations to determine user's position and time. The heart of the receiver/processor is a single channel receiver and TI 9900 microprocessor with 48 kbits of resident memory. The signal acquisition and tracking is accomplished by a combined early-late correlator with phase and frequency lock loops. Each of these functions is under the control of the microprocessor. Not shown in Fig. 4 is the battery pack which attaches to the receiver/processor. It contains two batteries which provide the required 24 vDC for the MVUE to be operated in the manpack configuration.

The antenna shown in Fig. 5 receives the simultaneous signals from all visible satellites. It contains only passive components which consist of two elements for the reception of the L_1 and L_2 signals. Each element has a right hand circular polarized far-field pattern and is omnidirectional in the upper hemisphere. The lower hemisphere response is minimized to reduce multipath.

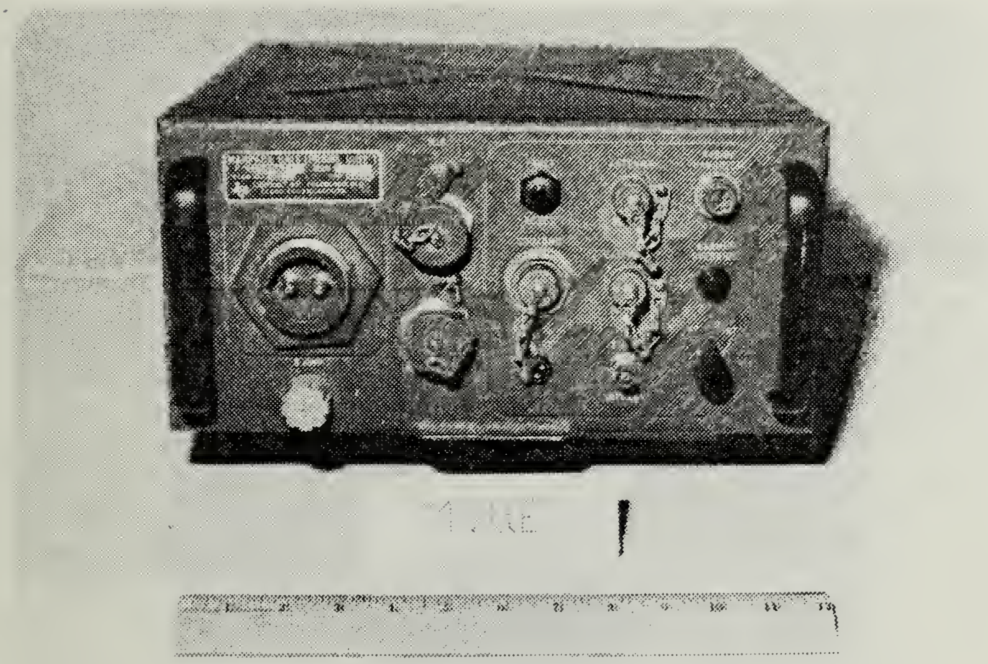

Fig. 4 Photograph of the MVUE Receiver

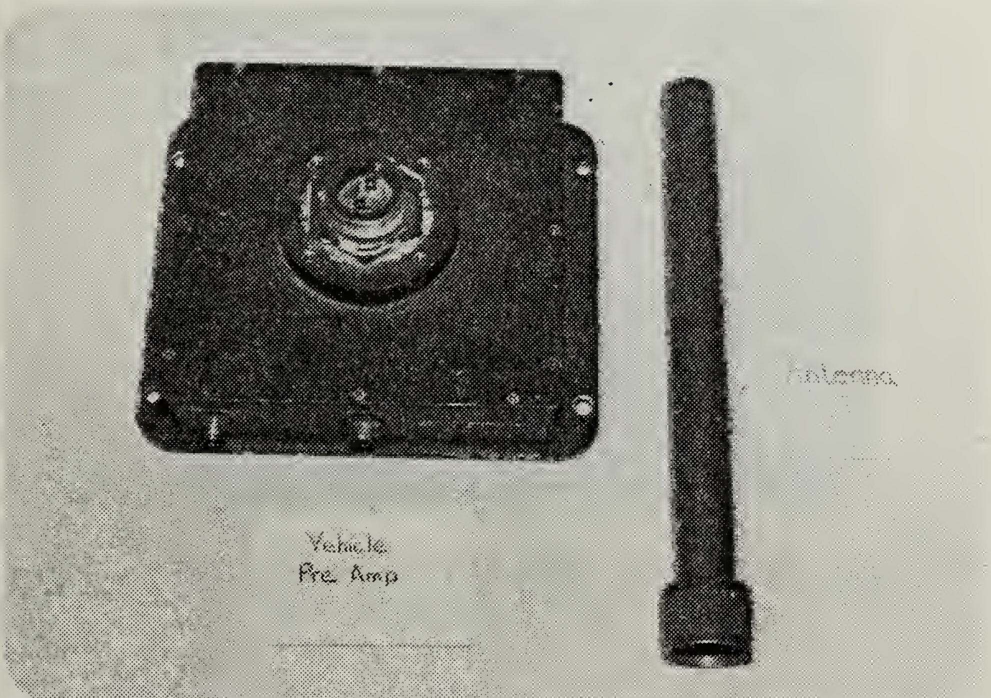

Fig. 5 Photograph of the MVUE Antenna and Vehicle Pre-Amp

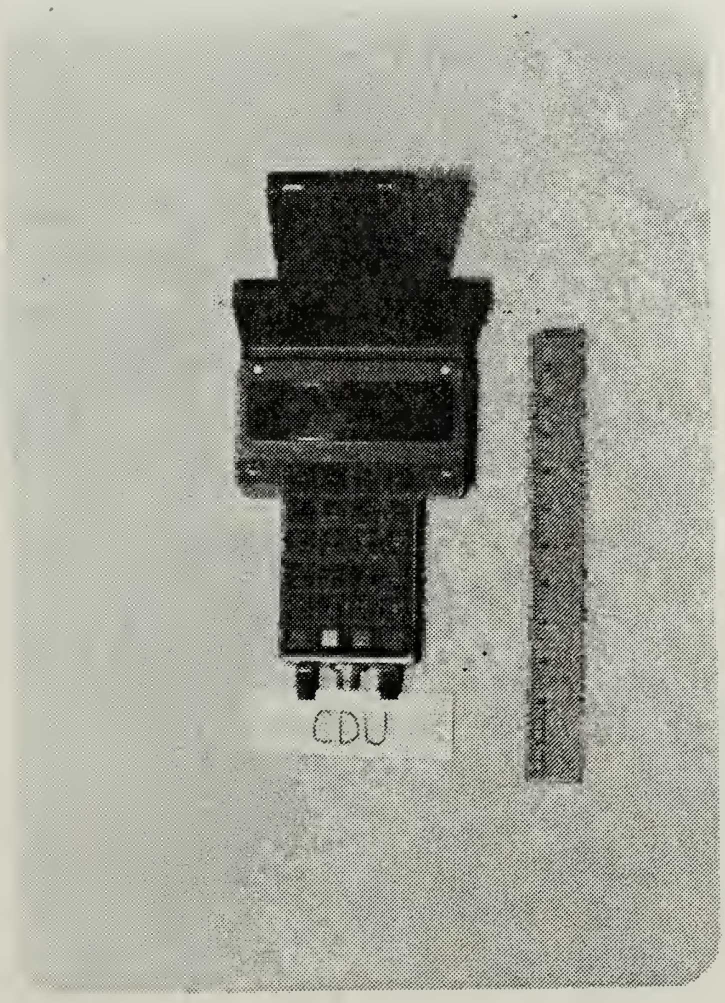

Fig. 6 Photograph of the MVUE Control Display Unit

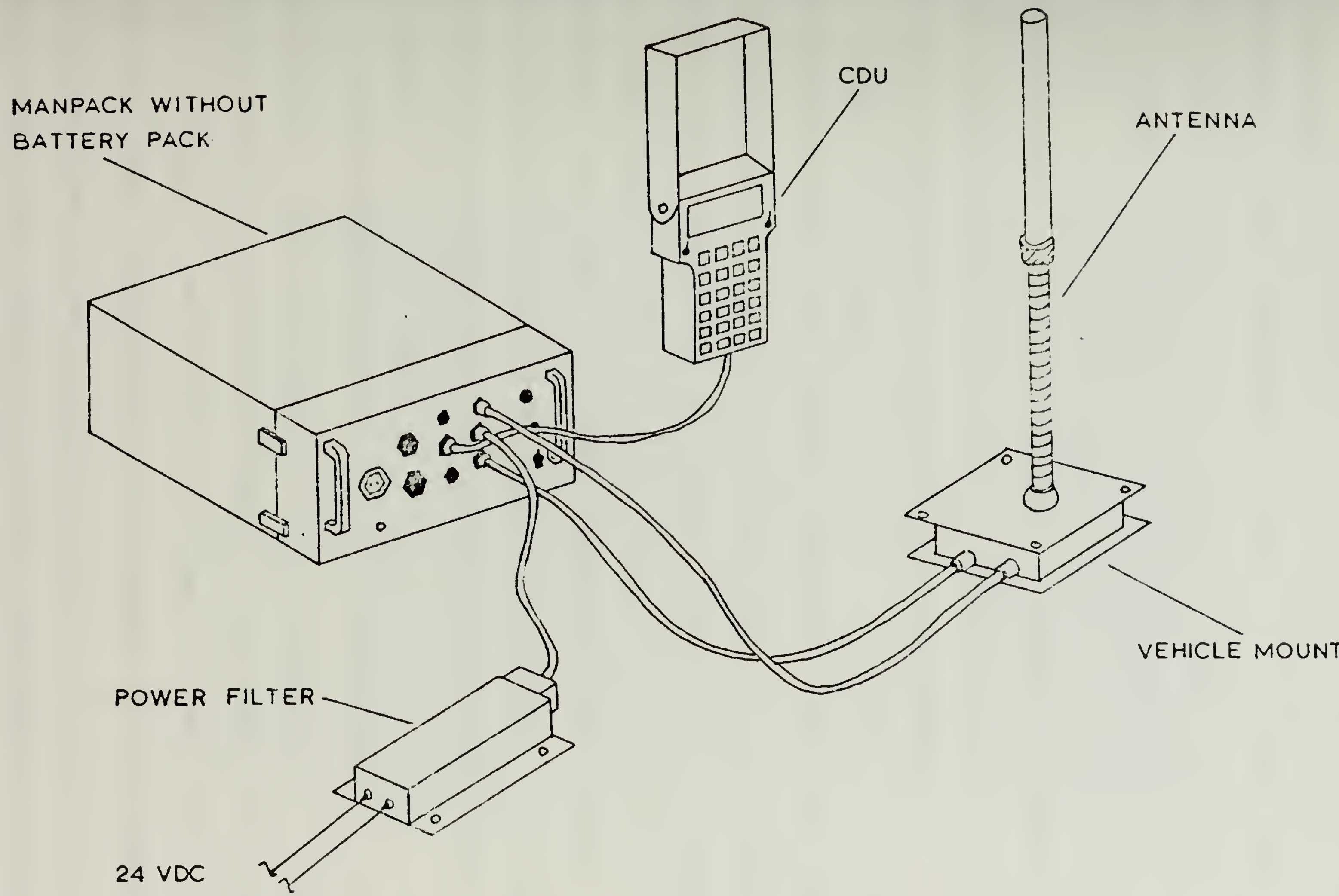

Fig. 7 Vehicle Installation Configuration

The vehicle pre-amplifier (Fig. 5) contains RF preconditioning hardware which is functionally the same as that contained in the receiver/processor. It is only used when the MVUE is operated in the vehicular mode. Its use permits the antenna to be placed in an optimum location on the host vehicle. In the manpack mode of operation, the antenna is placed directly on the receiver/processor. In addition to the vehicle pre-amp, the vehicle installation kit (VIK) includes a power filter and mounting tray hardware.

The Control Display Unit of Fig. 6 provides the interface between the user and receiver/processor. Its visual display is composed of two rows of ten alphanueric LED displays. A three level keyboard is provided for the user to respond to and enter data to the receiver/processor. A microprocessor monitors the keyboard for key depressions and formats the data from the receiver/processor for display. It is also capable of reformatting data to be sent by radio link using a digital message device.

For the demonstration, the MVUE was operated in the manpack mode. This configuration is shown in Fig. 8. Because of its weight and power restraints, the manpack was transported by vehicle. Note that the antenna is mounted on a flexible extension. This permits the antenna to be properly oriented when the receiver/processor is not standing up-right. Also used in the demonstration were two heavy-duty rechargeable batteries. These were substituted for the Lithium or Nickel-

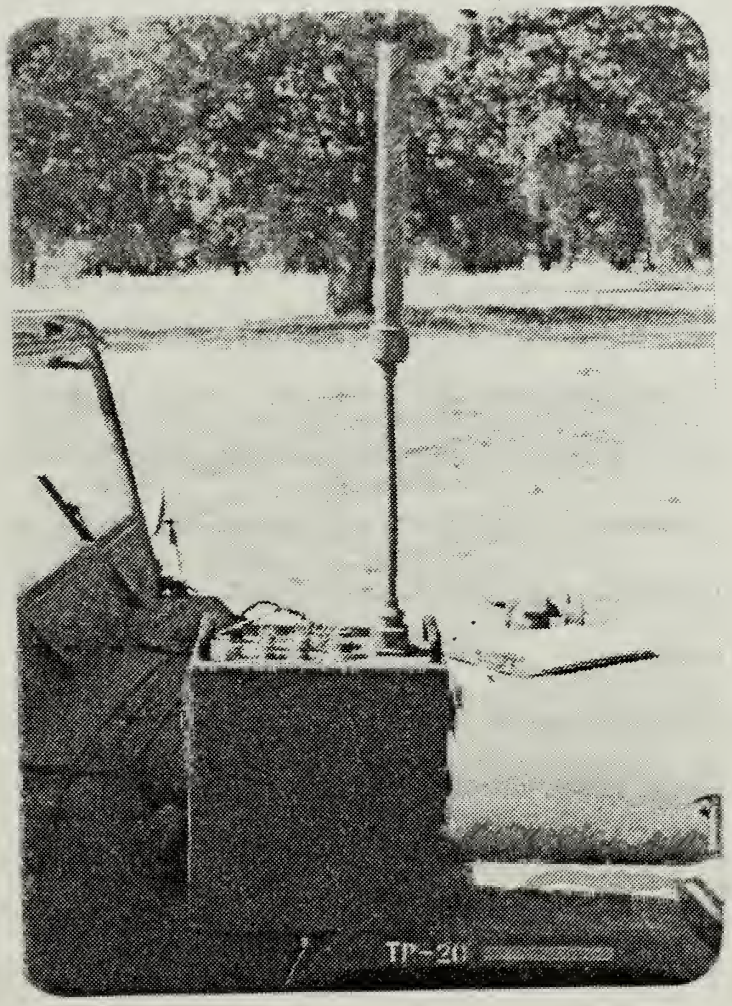

Fig. 8 Photograph of the MVUE

Cadium batteries normally used when the MVUE is operated in the manpack mode. The substitution was necessary because of the very high current drain of operating the receiver/processor continuously in the operate mode.

D. GENERAL AREA OF OPERATION

The GPS demonstration was conducted at Fort Hunter Liggett Military Reservation which is a highly instrumented field laboratory located 90 road miles south of Monterey, California. A number of independent studies have indicated that the geographic location of Fort Hunter Liggett offers the best combined terrain, weather and isolation to be found in the United States for the type of experimentation conducted by CDEC.

The reservation is irregular in shape averaging 11 miles in width and 26 miles in length of which 80% is usable for experimentation. The terrain varies from gently sloping valleys with little vegetation to rough mountainous areas with deep cross compartments to open valleys that are ideal for rapid cross-country movement. The Santa Lucia mountain range lies adjacent to the coast, and the crest roughly forms the western boundary of the reservation at approximately 3000 feet elevation. Paralleling this range are several lesser unnamed ranges which form the valleys of the San Antonio and Nacimiento Rivers. Maps of the the Nacimiento and Upper Milpitas Valleys, two major areas where the demonstration was conducted, are included in Appendix C.

E. SCENARIO OF DEMONSTRATION AND RESULTS

The demonstration was conducted during a five day period. The schedule was designed to subject the GPS receiver to different vegetation and terrain conditions each of the days while varying other parameters in an attempt to observe spacial or temporal dependence of error sources. The error sources of most concern were multipath and signal attenuation due to foliage.

The satellite visibility during the demonstration period permitted approximately two hours of operation when four or more satellites were 10° above the horizon. Appendix D includes computer predictions of satellite visibility for Fort Hunter Liggett. They include predictions of elevations angle, azimuth angle and a composite elevation-azimuth angle. Although the predictions are only computed for one day, the satellites have the same earth track but become visible 4 minutes and 3 seconds earlier each day. The charts in Appendix D were used to predict satellite visibility during the period 13-17 October 1980.

The daily ephemeris and clock corrections upload to the satellites occurred during the 30 minute period prior to four satellites becoming available. Prior to the actual operation with the MVUE receiver, a preliminary reconnaissance of the day's area of operation was conducted. This was to insure familiarity of the route for the driver and to verify the location of all survey points to be utilized for that day.

Approximately one hour prior to the availability of all the satellites, the MVUE receiver was transported to the first survey point. At this location an operational check of the receiver was conducted by the contractor technician. During the pre-test inspection, the various modes of operation were exercised to determine if the receiver was operating correctly.

An outline of the demonstration scenario is contained in Table 5.

Table 5 Demonstration Scenario

Day	Area	Nature of Test
1	Nacimiento Valley	Spoke Test
2	Upper Milpitas Valley	Unobstructed
3	Upper Milpitas Valley	Foliage & Vegetation(Obstructed)
4	Nacimiento Valley	Open & Obstructed
5	Nacimiento Valley	Static Text

A complete listing of the survey stations used and their survey data is included in Appendix E.

A list of all raw data taken is included in Appendix H. It includes readings taken prior to satellite upload and with less than the optimum number of satellites. Tables 6 through 10 are the reduced data from the demonstration and these were obtained by differencing the GPS readings from the surveyed reference. A summary of the statistics of the data taken during the five day demonstration is contained in Tables 11 and 12. The mean and standard deviation of the position

TABLE 6

REDUCED ERROR DATA - DAY 1

Reduced Error Data
Date: 13 October 1980 (Spoke Test)
Number of Data Point: 27

Ref. Pt	Δ distance From HL17	Δ Northing	Δ Easting	Δ Altitude	Time	Satellites	Remarks
HL17		3	4	24	19 34 34	5	Open
B	-18.6	-12	26	9	19 50 20	5	Open
	-3.6	2	24	5	19 57 02	5	
C	10	1	14	-5	20 08 14	5	Open
D	21	-2	22	4	20 12 22	5	Open
E	0	10	13	-5	20 33 20	5	Oak Canopy
	7	7	27	-1	20 73 10	5	
F	-7	2	24	-5	20 52 50	5	Open
G	-22.	8	34	-4	20 48 02	5	Open
H	-28	0	35	-8	20 57 50	5	Oak Canopy
I	-19.	-69	-56.	4	22 03 08	3	Open
J	-65	-69	-82	4	22 11 30	3	Open
K	7	9	18	2	22 00 22	5	Open
L	22	5	29	-17	20 05 08	5	Open
M	22	3	22	2	20 15 48	5	Open
N	6	10	24	-2	20 29 06	5	Partial
O	3	-7	27	-8	21 04 52	5	Open

NOTE: All numbers in meters

Ref. Pt	Δ distance From HL17	Δ Northing	Δ Easting	Δ Altitude	Time	Satellites	Remarks
P	-8	1	30	1	21 01 26	5	Open
Q	-41	15	41	67	21 28 12	4	Oak Canopy
R	7	-43	-17	4	21 53 12	3	Open
S	-28	-51	-31	4	21 57 56	3	Open
T	28	3	28	-11	20 19 56	5	Open
U	-16	16	13	4	21 13 10	5	Open
V	-16	15	8	-8	21 09 10	5	Oak Canopy
X	38	-7	38	-13	20 23 14	5	Oak Canopy
Y	14	12	26	2	21 23 00	5	Oak Canopy
W	-9	5	27	-5	21 18 14	5	Oak Canopy

TABLE 7

REDUCED ERROR DATA - DAY 2

Reduced Error Data
Date: 14 October 1980
Area: Upper Milpitas
Number of Data Points: 31

Ref. Pt	Δ Northing	Δ Easting	Δ Altitude	Time	No. of Sate	Remarks
BM198-14	-87	74	-346	20 01 04	4	
M77	35	2	39	20 08 42	4	
RM1	70	2	104	20 12 10	4	
RM2	41	-6.1	60	20 15 02	4	
M76	48	-28	19	20 21 18	4	NAVSTAR#2 Deleted
M75	-6	20	-11	20 51 24	4	All Points Exposed and
RM1	1	21	-11	20 52 30	4	
RM2	0	26	-18	20 54 46	4	
M74	1	3	-14.5	20 46 46	4	
RM1	-1	16.6	-29.5	20 47 34	4	
RM2	-6	15.4	-19.5	20 48 56	4	
M75	-6	20	-11	20 51 24	4	
RM1	1	21	-11	20 52 30	4	
RM2	0	26.4	-18	20 54 46	4	
M73						
RM1	1	27	-7	21 00 10	4	
RM2	-2.6	23	-15	21 01 58	4	

NOTE: All numbers in meters

Ref. Pt	Δ Northing	Δ Easting	Δ Altitude	Time	No. of Sate	Remarks
M74	-6.5	26.6	-19.5	21 06 46	4	Unobstructed
RM1	-8	23.6	-22.5	21 08 38	4	
RM2	-4	27.4	-21.5	21 10 58	4	
M75	-6	15	-22	21 13 28	4	
RM1	-3.9	24.5	-22	21 14 58	4	
RM2	-2.4	19.4	-27	21 16 24	4	
M76	-4.6	26.5	13	21 21 00	4	
M77	-1	32.5	1.2	21 28 38	4	
RM1	-5	26.3	-3.8	21 31 42	4	
RM2	-12	32.9	-5.8	21 30 28	4	
BM198.14	-23.2	26.8	19.6	21 40 28	3	
HL-8	-47.7	20.3	16	21 42 08	3	
M75	220.6	15.2	-60	20 29 24	4	Ephemeris Update in progress
2M1	-145.9	12.5	-239.01	20 32 50	4	
2M2	-201.4	-60.6	-345.01	20 34 58	4	

TABLE 8

REDUCED ERROR DATA - DAY 3

Reduced Error Data
Date: 15 October 1980
Area: Upper Milpitas Valley
Number of Data Points: 19

Ref. Pt	Δ Northing	Δ Easting	Δ Altitude	Time	*Satellites	Remarks
M62	.7	13.4	-15	18 55 06	4	
HL38	-66.6	172.9	-199	20 09 06	4	Medium Vegetation and Foliage
HL39	-33	54	-198.6	20 22 10	4	
M63						
RM1	-46.0	36.7	-210.8	20 34 56	4	
RM2	-42.2	36.7	-210.8	20 34 56	4	
M64	3.8	43.8	-250.4	20 41 54	4	
RM1	-76.1	34.8	-232.4	20 44 14	4	
M65	-81.7	17.4	-244.0	20 48 18	4	
RM2	-61.7	20.5	-536.0	20 49 52	4	
M66	-107.6	6.6	-514.0	20 54 32	4	
RM2	-110.8	-.5	-506.0	20 56 28	4	
M67	-94.7	-103.1	-467.6	21 11 56	4	
RM1	-110.6	-102.7	-490.6	21 13 10	4	
RM2	-82.6	-88.6	-453.6	21 09 38	4	

NOTE: All numbers in meters

Ref. Pt	Δ Northing	Δ Easting	Δ Altitude	Time	*Satellites	Remarks
M68	-122.1	-33.2	-521.2	21 01 08	4	coverage
RM1	-124.6	-38.5	-517.2	21 03 16	4	
RM2	-120.9	-56.0	-521.2	21 04 44	4	
HL37	-198.2	-120.6	8	21 30 46	3	
HL36	-272.1	-147.8	31.3	21 37 56	3	

*No ionospheric delay correction due to broken L_2 antenna connector

TABLE 9

REDUCED ERROR DATA - DAY 4

Reduced Error Data
Date: 16 October 1980
Area: Nacimiento Valley
Number of Data Points: 17

Ref.	Δ Northing	Δ Easting	Δ Altitude	Time	Satellites	Remarks
E-11	-178	-147	218	18 36 50	4	prior to upload
HL21	-180.6	-138.5	207.9	18 45 58	4	" "
HL18	-26.4	-22.9	-4.3	19 01 16	3	" "
HL17	-21.8	-22.2	-3	19 04 39	3	" "
HL22	15.3	-2.0	16.8	19 54 24	4	open
HL22 offset	13.0	2.0	-25	19 57 46	4	trees
HL20	9.3	3.6	-10.9	20 01 52	4	open
HL21	7.4	14.5	-9.1	20 09 52	4	open
HL22 offset	10.1	5.3	6.8	20 17 50	4	trees
HL22	6.3	7.0	1.8	20 19 46	4	open
HL18	5.6	9.0	2.7	20 25 48	4	open
HL17	5.2	16.8	-3.0	20 29 52	4	open
HL18	3.6	12.0	-2.3	20 36 08	4	open
HL22	6.3	15.0	4.8	20 41 46	4	open
HL22 offset	15.1	19.3	4	21 30 04	3	trees
HL20	12.3	12.6	-7.9	21 33 38	3	open
HL22	-68.6	-52.0	-2.2	21 55 00	3	open

NOTE: All numbers in meters

TABLE 10

REDUCED ERROR DATA - DAY 5

Reduced Error Data
Date: 17 October 1980
Area: Nacimiento Valley
Number of Data Points: 22

Ref. Pt	ΔNorthing	ΔEasting	ΔAltitude	Time	Satellite	Remarks
HL21	.4	23.5	-34.1	20 56 52	4	
HL21	4.4	17.5	-36.1	20 57 54	4	
HL21	6.4	23.5	-32.1	20 58 16	4	
HL21	5.4	22.5	-25.1	20 59 12	4	
HL21	6.4	33.5	-29.1	21 00 00	4	
HL21	-2.6	26.5	-32.1	21 00 08	4	
HL21	-6.6	27.5	-35.1	21 01 50	4	
HL21	-5.8	22.5	-34.1	21 02 32	4	Unobstructed
HL21	1.4	26.5	-40.1	21 03 14	4	
HL21	5.4	20.5	-36.1	21 04 07	4	
HL21	-2.6	27.5	-39.1	21 04 02	4	
HL21	-2.6	21.5	-34.1	21 05 24	4	
HL21	1.4	17.5	-36.1	21 06 06	4	
HL21	-1.6	18.5	-27.1	21 06 48	4	
HL21	-1.6	21.5	-39.1	21 07 20	4	
HL21	-.6	23.5	-34.1	21 08 14	4	
HL21	-2.6	25.5	-32.1	21 08 56	4	
HL21	-3.6	29.5	-38.1	21 09 38	4	

NOTE: All numbers in meters

Ref. Pt	Δ Northing	Δ Easting	Δ Altitude	Time	Satellite	Remarks
HL21	-6.6	23.5	-39.1	21 10 20	4	
HL21	-12.6	17.5	-38.1	21 11 22	4	
HL21	-6.6	27.5	-43.1	21 11 44	4	
HL21	-8.6	20.5	-44.1	21 12 28	4	
HL22	8.3	14.0	-9.1	19 54 02	4	lightly wooded
HL22 offset	14.1	28.3	-44.1	20 25 14	4	heavy canopy
HL22 offset	15.1	33.3	-15.1	20 26 56	4	of oak trees (see photo in section VI A-5)
HL22 offset	14.1	28.3	-22.1	20 27 52	4	
HL22 offset	11.1	27.3	-25.1	20 28 48	4	
HL22 offset	6.1	25.3	-38.1	20 29 34	4	
HL22 offset	9.1	27.3	-35.1	20 30 54	4	
HL22 offset	7.1	28.3	-37.1	20 31 50	4	
HL22 offset	6.1	28.2	-24.1	20 32 46	4	
HL22 offset	7.1	23.3	-25.1	20 33 52	4	
HL22 offset	7.1	25.3	-26.1	20 34 50	4	
HL22 offset	6.1	24.3	-31.1	20 35 46	4	

Ref. Pt	Δ Northing	Δ Easting	Δ Altitude	Time	Satellite	Remarks
HL22 offset	6.1	27.3	-30.1	20 36 54	4	
HL22 offset	11.1	24.3	-35.1	20 38 00	4	
HL22 offset	6.1	17.3	-41.1	20 38 56	4	
HL22 offset	3.1	34.3	-37.1	20 39 52	4	
HL20	.3	18.6	-43.9	20 46 36	4	open terrain
HL17	-18.8	15.8	-3.0	21 27 22	3	Sparse trees rolling terrain
HL17	-20.8	14.8	-7.0	21 28 30	3	
HL17	-11.8	16.8	-5.0	21 29 12	3	
HL17	-2.8	23.8	-5.0	21 29 54	3	
HL17	3.2	33.8	-5.0	21 30 36	3	
HL17	-11.8	18.8	-2.0	31 31 18	3	
HL17	-----delete-----					
Number of Data Points: 7						
HL18	-32.4	-13.9	-6.3	21 35 40	3	Sparse trees rolling terrain
HL18	-23.4	-1.0	-7.3	21 36 32	3	
HL18	-29.4	-7.0	-6.3	21 37 00	3	
HL18	-10.4	15.0	-6.3	21 37 46	3	
HL18	-27.4	3.0	-6.3	21 38 28	3	
HL18	-8.4	12.0	-8.3	21 39 10	3	

Ref. Pt	Δ Northing	Δ Easting	Δ Altitude	Time	Satellite	Remarks
HL18	-26.4	-3.0	-3.3	21 39 52	3	
HL18	-23.4	10.0	-6.3	21 40 34	3	
Number of Data Points: 8						
HL22	-42.6	-30.0	2.8	21 46 48	3	lightly covered w/trees
HL22	-56.6	-42.0	1.0	21 47 10	3	
HL22	-49.6	-18.0	-.15	21 47 52	3	rolling terrain
HL22	-67.6	-48.0	1.8	21 48 34	3	
HL22	-35.6	-14.0	-.15	21 49 16	3	
HL22	-43.6	-27.0	1.0	21 49 58	3	
HL22	-61.6	-44.0	1.0	21 50 40	3	
HL22	-70.6	-61.0	1.0	21 51 22	3	

error and the maximum and minimum recorded errors from the reference are listed. Table 11 includes data taken throughout the five day period but only includes data which were obtained from four satellites. Table 12 includes only data from Day 5 but only three satellites were used in the determination of position data. Known altitude data was used in the position determination. The data used for both tables was obtained only after all satellites were uploaded with their daily ephemeris and clock corrections parameters.

Day 1 of the demonstration was conducted at and in the vicinity of survey point HL 17. The test conducted is referred to as the Spoke Test because concentric circles with varying radii were constructed about HL 17. Then various locations along the perimeter of each circle were marked and the survey data for that point determined. A diagram of the spoke test pattern and the surveyed points used is included in Appendix G. The points chosen included both unobstructed and obstructed areas due to vegetation. Figure 9 and 10 show characteristic terrain and vegetation in the vicinity of the spoke test. The location of the Spoke Test was chosen because of the extremes of vegetation and because the surrounding terrain did not present a masking problem. The objective of the spoke test was two fold. First by remaining in one general location (greatest position change 200 meters) for the entire period, it was hoped that terrain dependent errors would remain fixed for all data and other error sources could

Table 11 Summary of Data--Four Satellites

	Statistics	ΔDistance	ΔNorthing	ΔEasting	ΔAltitude	#points	Remarks
Day 1	Mean	.022	3.9	23.6	1.2	24	MVUE selected satellites, included NAVSTAR #2 Spoke Test
	Std. Dev.	18.8	7.2	9.0	15.9		
	High	38.0	16.0	41.0	67.0		
	Low	-41.0	-12.0	4.0	-17.0		
Day 2	Mean		-3.4	22.6	-12.0	24	NAVSTAR #2 deleted. Reference points were exposed and unobstructed
	Std. Dev.		3.6	6.5	12.1		
	High		1.0	32.9	13.0		
	Low		-12.0	3.0	-29.5		
Day 3	INVALID DATA						No ionospheric delay correction
Day 4	Mean		8.2	8.3	-1.74	10	Both exposed and unexposed Ref. points used
	Std. Dev.		3.5	5.9	10.8		
	High		15.3	16.8	16.8		
	Low		3.6	-2.0	-25		
Day 5 (HL21)	Mean		-1.5	23.5	-35.4	22	Static test unobstructed
	Std. Dev.		5.0	4.1	13.9		
	High		6.4	33.5	-25.1		
	Low		-12.6	17.5	-44.1		
Day 5 (HL22 Offset)	Mean		8.6	26.8	-31.1	15	Static test heavy foliage and vegetation
	Std. Dev.		3.5	3.9	7.8		
	High		15.1	34.3	-15.5		
	Low		3.1	17.3	-44.1		

All numbers are in meters

Table 12 Summary of Data--Three Satellites

	Statistics	ΔDistance	ΔNorthing	ΔEasting	ΔAltitude	#points	Remarks
Day 5 (HL17)	Mean		-12.9	18.8	-4.6	7	Sparse Vegetation
	Std. Dev.		9.9	7.6	1.5		
	High		3.2	33.8	-2.0		
	Low		-27.8	7.8	-7.0		
Day 5 (HL18)	Mean		-22.6	1.9	-6.3	8	Sparse Vegetation
	Std. Dev.		8.2	9.3	1.3		
	High		-8.4	15.0	-3.3		
	Low		-32.4	-13.9	-8.3		
Day 5 (HL22)	Mean		-53.5	-31.7	1.0	8	Sparse Vegetation
	Std. Dev.		11.8	15.0	.8		
	High		-35.6	-14.0	2.8		
	Low		-70.6	-61.0	-.15		

All numbers are in meters

Fig. 9 Photograph Taken in Vicinity of HL 17--Unobstructed

Fig. 10 Photograph Taken in Vicinity of HL 17--Obstructed

be identified. Secondly, the spoke pattern test established a secondary grid coordinate system (reference HL 17) which could be used to characterize general position accuracy of GPS. The receiver on Day 1 was permitted to select the satellites it would use in the determination of position. It included NAVSTAR 2 in the satellites selected. Information obtained after the first day of the demonstration indicated that the unstable clock of NAVSTAR 2 would significantly affect position accuracy if used in the determination. This was borne out by the data taken on Day 1. Because of this, NAVSTAR 2 was not used by the receiver on Days 2, 3, 4 and 5. The first column (Table 11) on Day 1 (Δ Distance) is the amount of error of the GPS data from the actual distance from the reference (HL 17). This figure is an indication of how accurate GPS is at predicting the relative distance between two points.

Day 2 of the demonstration was conducted in the Upper Milpitas area. The survey points were all located along a high exposed ridge line. Surrounding vegetation and foliage presented little or no problem to the reception of satellite signals and the high elevation aided the acquisition and tracking of the signals. This should have permitted optimum performance of the receiver. Pictured in Figure 11 is terrain similar to that used during Day 2. Also on Day 2, the receiver was taken to two other areas. The receiver was operated in both areas prior to the availability of all the

Fig. 11 Unobstructed Terrain Used on Day 2

satellites in an attempt to observe the effects of dense vegetation and severely masking terrain on the acquisition of the satellite signals. Pictures of the two locations chosen are shown in Figures 12 and 13. The statistics on Day 2 data indicate some improvement over Day 1, and this is thought to be due primarily to the deletion of NAVSTAR 2.

Day 3 was also conducted in the Upper Milpitas area. The survey points were located throughout the valley and generally presented an obstructed view due to both terrain and vegetation. The objective of Day 3 was to determine the effect of terrain and vegetation on navigation accuracy. It was hoped this could be done by comparing the position accuracy of Day 2 (no terrain or vegetation masking) with that of Day 3 (significant terrain and vegetation masking). Data obtained on Day 3 varied tremendously and did not represent the position accuracy obtained on Days 1 and 2. Closer examination of the data and of the receiver at the conclusion of the day indicated there was a problem with the receiver. It was found that a connector on the L_2 antenna was not properly connected and this caused only the reception of the L_1 signal. This resulted in no ionospheric delay correction being made to the calculated slant range and thus an inaccurate position calculation. The data collected on Day 3 was determined to be invalid. The problem was corrected for the remaining days of the demonstration.

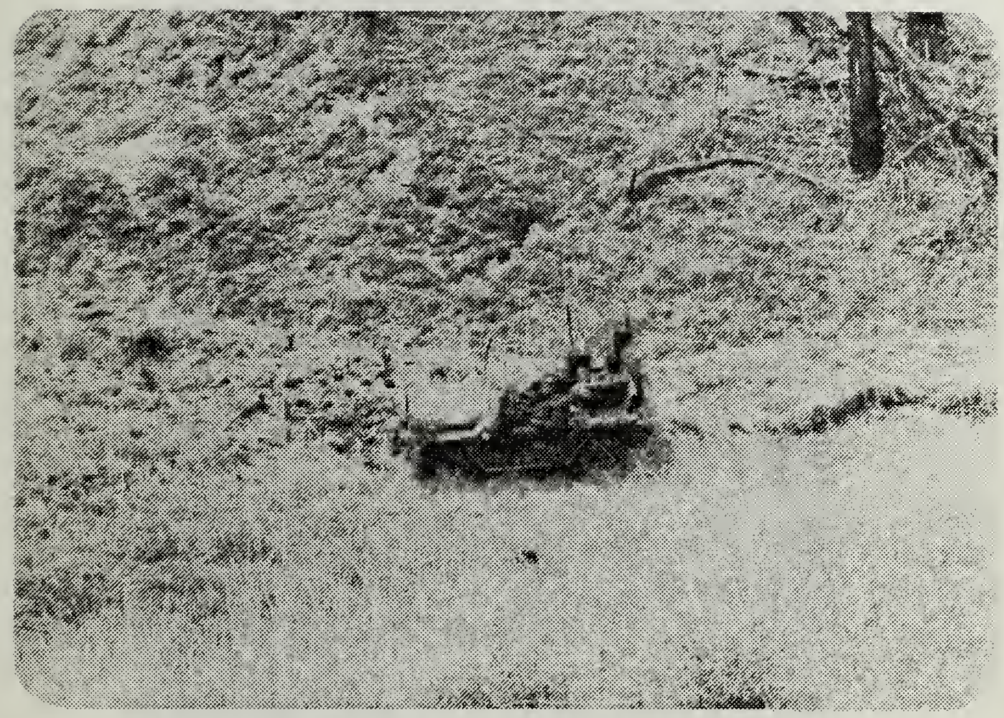

Fig. 12 Masking Position Used on Day 2

Fig. 13 Position of Heavy Vegetation Used on Day 2

The remainder of the demonstration was conducted in the Nacimiento Valley. The same few selected survey points were utilized for both days. They included several open and obstructed points. Pictured in Fig. 14 is one of the surveyed points (HL 22 offset) which was utilized on both days. The demonstration on Day 4 consisted of taking single-position readings from consecutive points. The process was repeated several times over the entire period the satellites were available. The objective of this procedure was to determine the effect of satellite movement (Geometric Dilution of Precision) on position accuracy. Day 5 consisted of static tests conducted at each survey point. Multiple consecutive position readings were taken at each survey point over an extended period of time. The objective of this procedure was to allow the receiver's data smoothing filter (Kalman Filter) to completely converge and determine its effects on position accuracy. Data obtained on these days indicated a gradual increase in position accuracy through the midpoint in the satellite availability period. A similar decrease after the midpoint had been reached was also experienced. This effect was attributed to the changing satellite GDOPs.

Generally, the data obtained throughout the demonstration agreed with similar recently conducted tests, the most recent of which was a demonstration of GPS in Europe during October 1980 for NATO military leaders. The terrain and vegetation at Fort Hunter Liggett had little or no discernible effect on

Fig. 14 HL 22 Offset Used on Days 4 and 5

satellite acquisition or tracking. The specific attempts to interfere with satellite acquisition through terrain and vegetation masking were unsuccessful. Only once, during Day 4 of the demonstration, did the receiver lose track of any satellite in the middle of the satellite availability period. The receiver lost track when it was being positioned under heavy vegetation but reacquired when moved out into the open. A successful position determination was then obtained under the vegetation. A rule of thumb which developed out of Phase I testing of GPS indicated that receivers were capable of acquiring, tracking and navigating if any sky was visible through the vegetation. The results of the Fort Hunter Liggett demonstration support this rule of thumb.

V. CONCLUSIONS

The NAVSTAR/Global Positioning System does have potential for use in RTCA experiments as the PL system on instrumented ranges. The demonstration of GPS at Fort Hunter Liggett showed that an accuracy of 10-15 meters root sum squared should be expected from the operational system. The prototype receiver which was used for the demonstration met all of the manufacturer's specifications which were examined and considered important for use in RTCA experiments. Second generation receiver equipment which must be more compact, lighter and meet stricter specifications will shortly begin Phase II testing at Yuma Proving Ground.

Although the position accuracies of GPS are not as good as RMS, there are important advantages which must be considered. GPS has an inherent advantage over RMS in the determination of altitude because the satellites are not in the same plane as the user, as is the case with RMS. Even the limited amount of data from the demonstration supports the superiority of GPS over RMS in this category. Another very important advantage of GPS is that an unlimited number of users may use the system and all may do so concurrently without interference or difficulty. This would permit unlimited number of players in concurrent experiments. GPS as a position/ location system can also be characterized as exportable

because of its world-wide availability. These three characteristics of GPS: (1) large player capacity, (2) ability to perform concurrent experiments, and (3) exportability are designated by CDEC as critical unmet requirements of the current position/location system. Finally as a by-product of using GPS, the user has access to the very accurate GPS time which may be used to advantage.

There are also disadvantages in considering the use of GPS. Although more accurate in the z direction, RMS is more accurate in the x-y plane. This will not change as GPS becomes operational. Another limitation of GPS is its ability to frequently update a user's position. RMS is capable of position updates many times a second where as GPS is only capable of once every 1.5 seconds at best. Finally, because GPS is a new system and still undergoing testing, it will not be until 1987 that the system will become fully operational.

In considering the advantages and disadvantages of the system mentioned, it is apparent that there does exist a potential for use of GPS on instrumented ranges. More study and further tests are needed to determine the extent of that potential.

APPENDIX A

ARCHITECTURE OF RANGE MEASURING SYSTEM

A. TECHNICAL DESCRIPTION

1. Theory of Operation

The PL system used at Fort Hunter Liggett is a pulse code modulation-amplitude modulation (PCM-AM) system. It determines a player's position by a multilateration process based on the measurements of range between known locations and the player. Fig. 15 depicts the geometry of the process.

The first function is to determine range data for various A-station and B unit combinations. RMS accomplishes this via the PCM-AM subsystem operating at 918 MHz. The C-station receives parallel output commands from a computer and converts them to serial form for relay to the field units. The commands may be either ranging or digital messages. They are coded with A and or A-stations and B unit addresses which determine the particular path a command will take. The range commands instruct addressed A stations to obtain a range reading on the particular addressed B unit. The B unit response travels the same path back to the C-station, via the A-station, where it is converted back to parallel form for computer usage.

The range is computed by the A-station measuring the elapsed time for a fast rise time pulse to propagate from the A-station to the B unit and back again. The round trip time

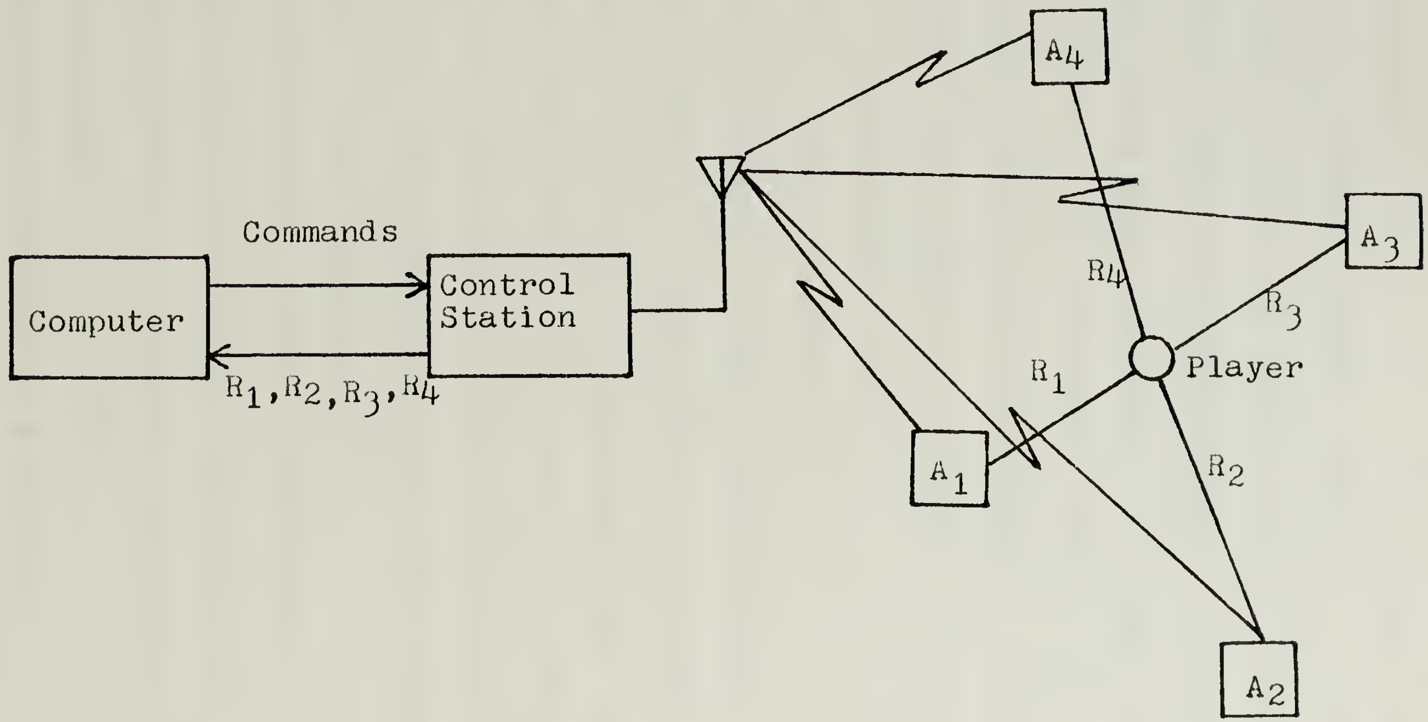

Fig. 15 Geometry of Multilateration

is measured by a 75 MHz counter in the A-station and therefore has a resolution of two meters. The counter can accomodate a 17 bit message and thus the maximum range an A-station can report is 262.143 meters. The A-stations and B units use leading edge detection/threshold circuits to receive the range pulse and can measure the range between any A station and B unit to an accuracy of 3 meters [Ref. 5].

The ordering, addressing and frequency of interrogation of an A station for ranges to specific B units occur in accordance with the particular software utilized in the C station's computer. The C station, for example, may be directed to interrogate every B unit through every A station, recycling a given number of times within a specified time frame. Or it can be directed to interrogate selected B units through selected A stations. This flexibility permits various polling schemes to be tailored to the characteristics of individual players, e.g. frequent polling for high dynamic players and slow polling for low dynamic players.

The PL data on each player is recorded so it is available at some post-trial time or immediately for feedback on the field experiment via the display subsystem or for inputs to other processes such as RTCA.

It is possible to enhance the PL data if it is to be used for post-trial analysis. The enhancement makes use of an interpolative technique which uses position data from both before and after the time of interest to estimate the state

of the system [Ref. 6]. If the PL data is to be used in real time for such processes as RTCA, then another technique to obtain smooth reasonable PL information is used. This enhancing technique (filtering) uses only position data up to the time the state of the system is to be estimated. The state of the system here means a player's position, velocity or acceleration. The filter used in RMS is a Kalman filter.

The performance of the Kalman filter in RMS is crucial to the overall performance of RMS. Depicted in Fig. 16 is a model P of RMS indicating the position of the Kalman filter in the PL subsystem of RMS.

The filter provides a smooth reasonable estimate of the state of the player, e.g. position, velocity or acceleration. In theory, a Kalman filter is an optimal estimator and consists of a computational algorithm that processes measurements to deduce a minimum error estimate. In the case of the Kalman filter used in RMS at Fort Hunter Liggett, the minimum error estimate is in the least squares sense. The filter algorithm computes the minimum error estimate of the states through knowledge of the system and measurement dynamics, assumed statistics of the system noises and measurement errors and initial condition information [Ref. 8].

The six state Kalman filter is most frequently used at Fort Hunter Liggett. In this mode of operation, the filter provides estimates of position and velocity, x, y, z and $\dot{x}$, $\dot{y}$, $\dot{z}$. The filter may also be operated in a three state

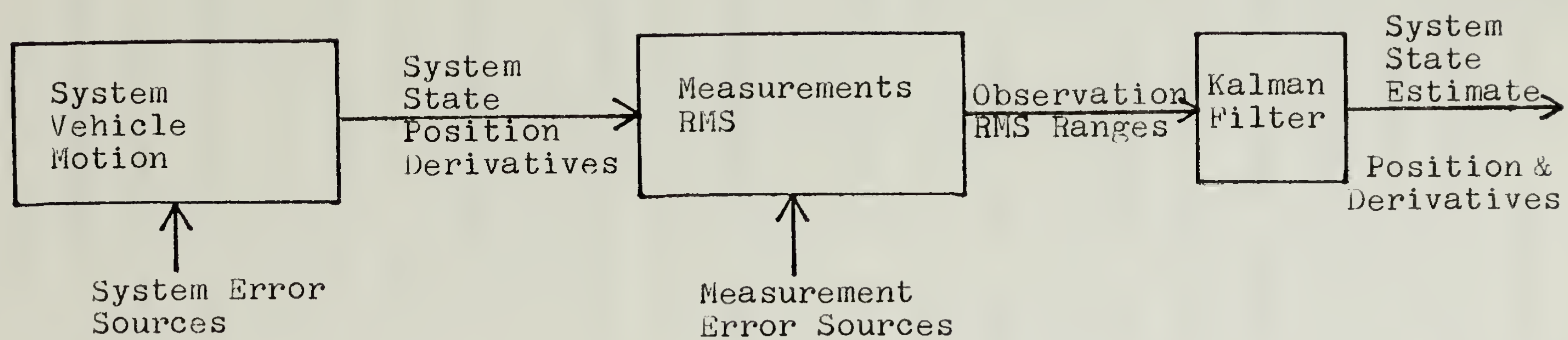

Fig. 16 Model of RMS Including Kalman Filter [Ref. 7]

mode providing only positional information as well as a nine state mode. The nine state mode also gives estimates of player acceleration in addition to position and velocity data.

Figs. 17, 18 and 19 graphically depict the six state Kalman filter process for a normal range update. Accounting for the most recent estimate of position and velocity in each coordinate (the state of the player, the variance and co-variance of the variables) and the maximum expected acceleration, the Kalman filter predicts the range from the player's predicted position of the B-unit from the A-station and establishes range editing criteria. As shown in Fig. 18 the measured range is then compared to the predicted range. Taking into account the variances of each, a "best" range, which minimizes each of the new variances and co-variances, is selected. This procedure is repeated for each A-station which reported a range to the particular B-unit during this cycle. Given reasonable range data the filter's algorithm converges quite rapidly [Ref. 9]. Notice that the range from A-station 3 has been rejected as a "wild range" because it falls outside of the editing criterion. The editing criterion is established as part of the a priori knowledge the filter must have to function properly. In the case of RMS, the filter must have knowledge of the following: 1) A-station geometry, 2) the accuracy of the RMS ranges and their expected error distribution and 3) the model error. The model error describes factors which will cause the state

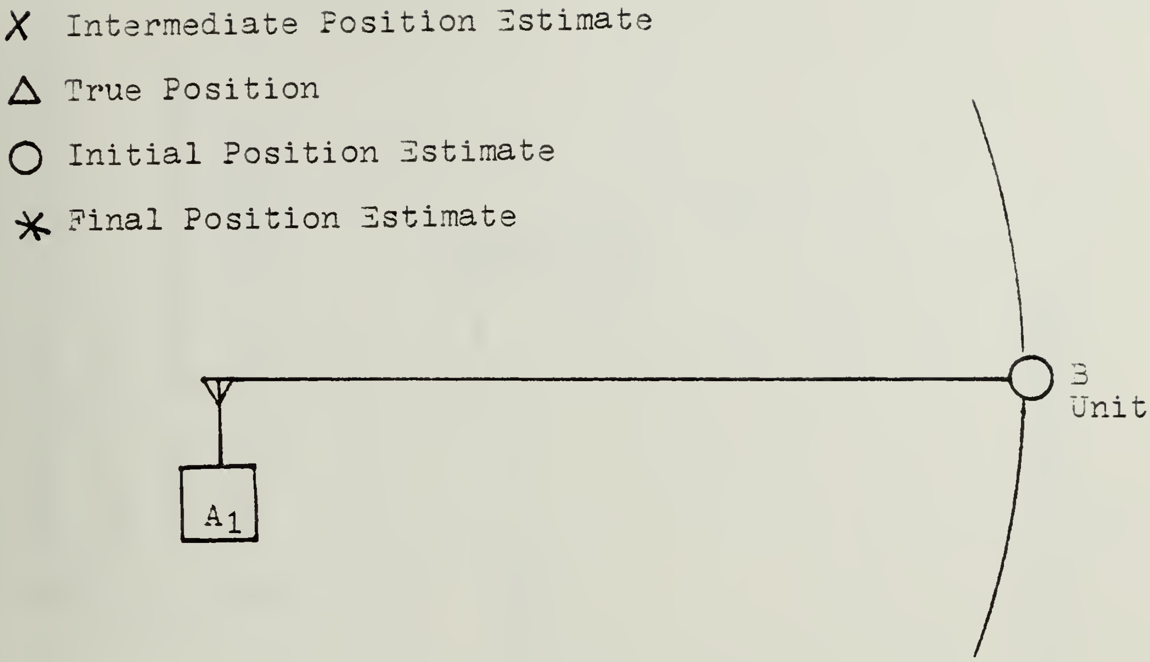

Fig. 17 Predicted Range From A-Station to B Unit

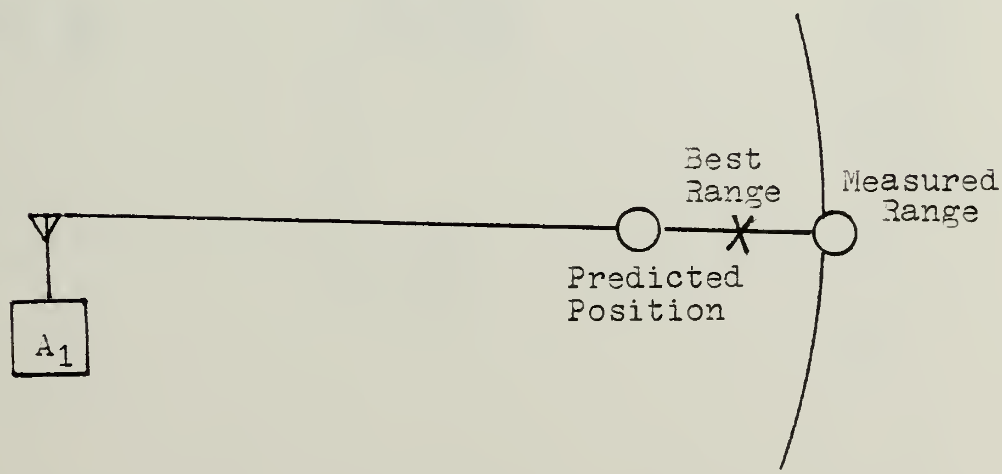

Fig. 18 The Best Compromise Between the Predicted and Measured Ranges Selected for A-Station

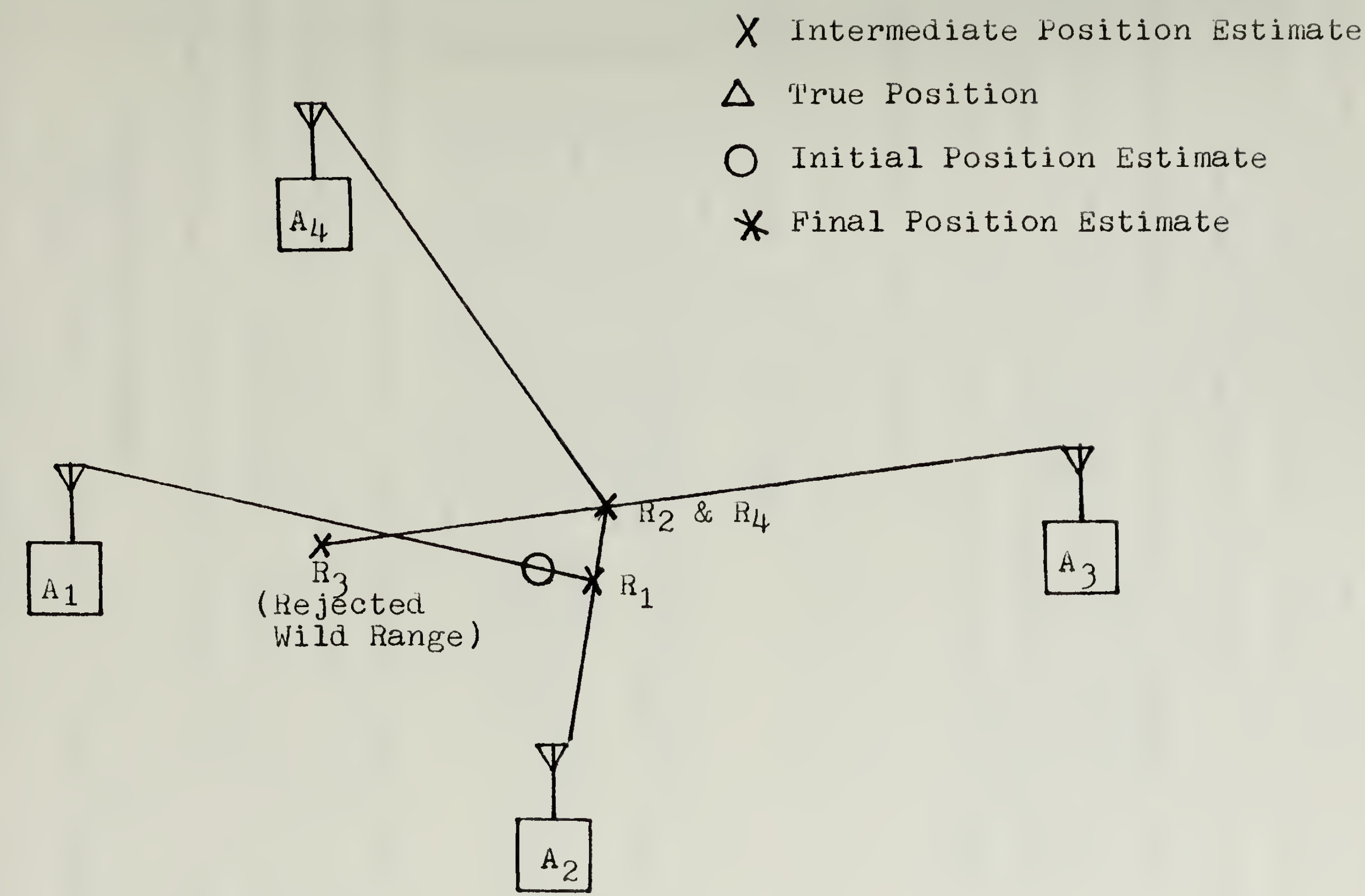

Fig. 19 Final Kalman PL Solution Combining Ranges From A-Stations 1, 2, 3 and 4

to become more uncertain with time. In the case of a six state filter where only player position and velocity are being estimated, the model error would be the maximum expected acceleration. The editing criterion would be set at some level and data falling outside the editing level would be rejected. The criterion depends on the perceived quality of the last estimate and the time since the last estimate times the model uncertainty.

The six state filter used in the Fort Hunter Liggett system combines the following:

1. Player past PL
2. The error estimate of that position
3. The error estimate of the incoming data
4. The player's velocity
5. The error estimate of that velocity
6. The player's maximum expected acceleration
7. The time interval since the last estimate
8. The physics of permissible motion
9. Dynamic range editing

Experience with the six state Kalman filter indicates that the above parameters and the acceleration error model can be manipulated in a predictable, intuitive way to obtain a balance between smooth continuous data and accuracy.

2. Functional Elements

Although RMS is primarily a PL and telemetry system, it is made up of several subsystems which contribute to its primary function or enhances its operation. There are four major subsystems in RMS. They are 1) Tracking and Communication subsystem (TCS), 2) Airborne Instrumentation Subsystem (AIS), 3) Computation Subsystem (CS) and 4) Display Subsystem. Fig. 20 is a typical RMS deployment showing the four major subsystems.

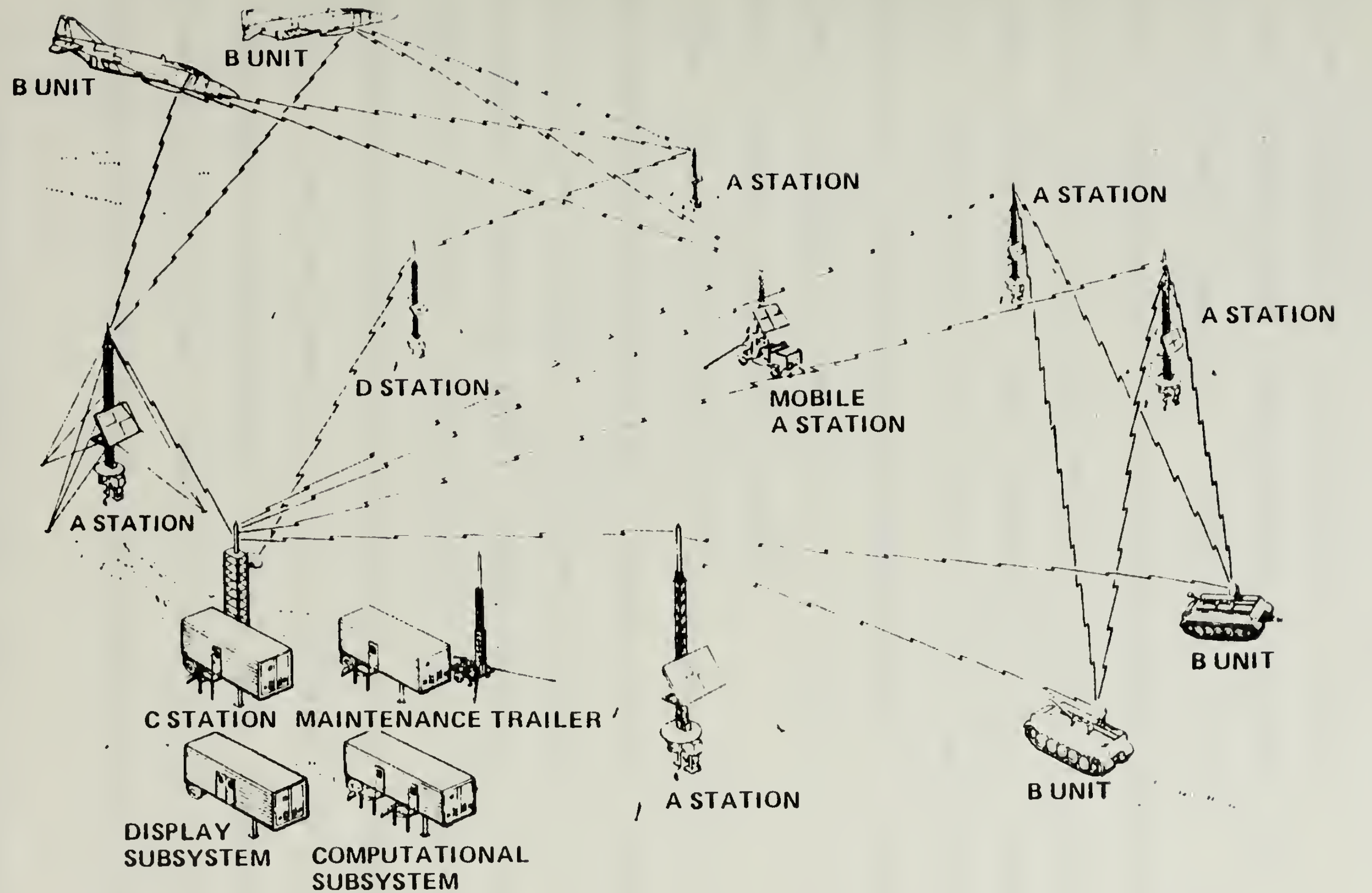

Fig. 20 Deployment of 4 Subsystems of RMS

The following is a brief discussion of the four major subsystems; a more detailed description of the elements which make up the PL portion of the system will follow.

The Tracking and Communication Subsystem (TCS) consists of four major elements: A-stations, B units, a C-station and A/D stations. This subsystem does the actual ranging between the A stations and the players carrying B units. The range data is then returned to the C station where it is collected and processed for re-transmission. Additionally, this subsystem has the function of passing communication messages to and from the B units via the A stations on request from the C station.

The Airborne Instrumentation Subsystem (AIS) is used only when additional information is needed on the flight dynamics of player aircraft. Three-axis attitude, air speed, angle of attack, side-slip angle, accelerations, air speed and PL data are possible using AIS which consists of an instrumentation pod mounted in a standard AIM-9 Sidewinder missile body. The instrumentation pod contains a microcomputer, gryoscopes, accelerometers and a B unit transponder. The system requires two way communications and 20 to 100 seconds to initialize before providing position and attitude data.

The Computation Subsystem (CS) receives range data, aircraft attitude data and laser-pairing messages from the TCS. The range and attitude data is processed by Kalman

filter algorithms. The resulting PL data along with the pairing messages are used by weapons simulation routines to determine real time casualty assessment. The computation subsystem hardware at Fort Hunter Liggett is housed in a permanent facility.

After processing in the computation subsystem, data is passed in real time to the Display Subsystem where it is displayed for evaluation by range personnel. Data storage capability permits range personnel to record experiment data for post trial analysis and evaluation.

3. Major Components of TCS

The Tracking and Communication Subsystem is the backbone of RMS. Its components are required to perform at near capacity and flawlessly for the duration of an experiment. Many of the subsystem's components are subjected to the sometimes harsh Fort Hunter Liggett environment. Many of this system's components must be durable enough to be carried by track vehicles and aircraft while also being compact and light-weight enough to be carried by personnel. Because a slight degradation in the components of the TCS have such a significant influence on the overall performance of RMS, a more detailed description of their structure is presented.

a. C-Station

The controller of the TCS is the master control station (C-Station). It provides the command and communications link with the various participants and obtains positional

information under its own computer control. By the very nature of its two functions, communication and control, the C-station can logically be divided into two portions. Diagrammed in Fig. 21 is the communications segment. This segment provides the communications between A stations and the C station as well as the communications between the C station and the computation subsystem (CS) via the computer data link (CDL). A Varian 73 (V-73) computer controls the communication segment within the C station and functions as the RMS driver and data buffer. The Varian 73 computer is a 16 bit machine, with 64K bits of memory and 330 ns cycle time [Ref. 11]. The important functions of the C station are listed below.

1. Accept C station commands from the Computation Subsystem.
2. Control the communications segment of the C station.
3. Format and buffer sent and received RMS responses.
4. Provide timing.

Timing is one of the very important functions of the C station. The data are time tagged as they pass through the C station which facilitates post experiment analysis.

b. A/D Station

An A station is a semi-fixed radio link between the C station and player carried B units. Upon request, it will measure the slant range between itself and a selected B unit. It also relays two way digital messages between the B units and the C station. The A station's major components consists of a radio frequency (RF) receiver and transmitter,

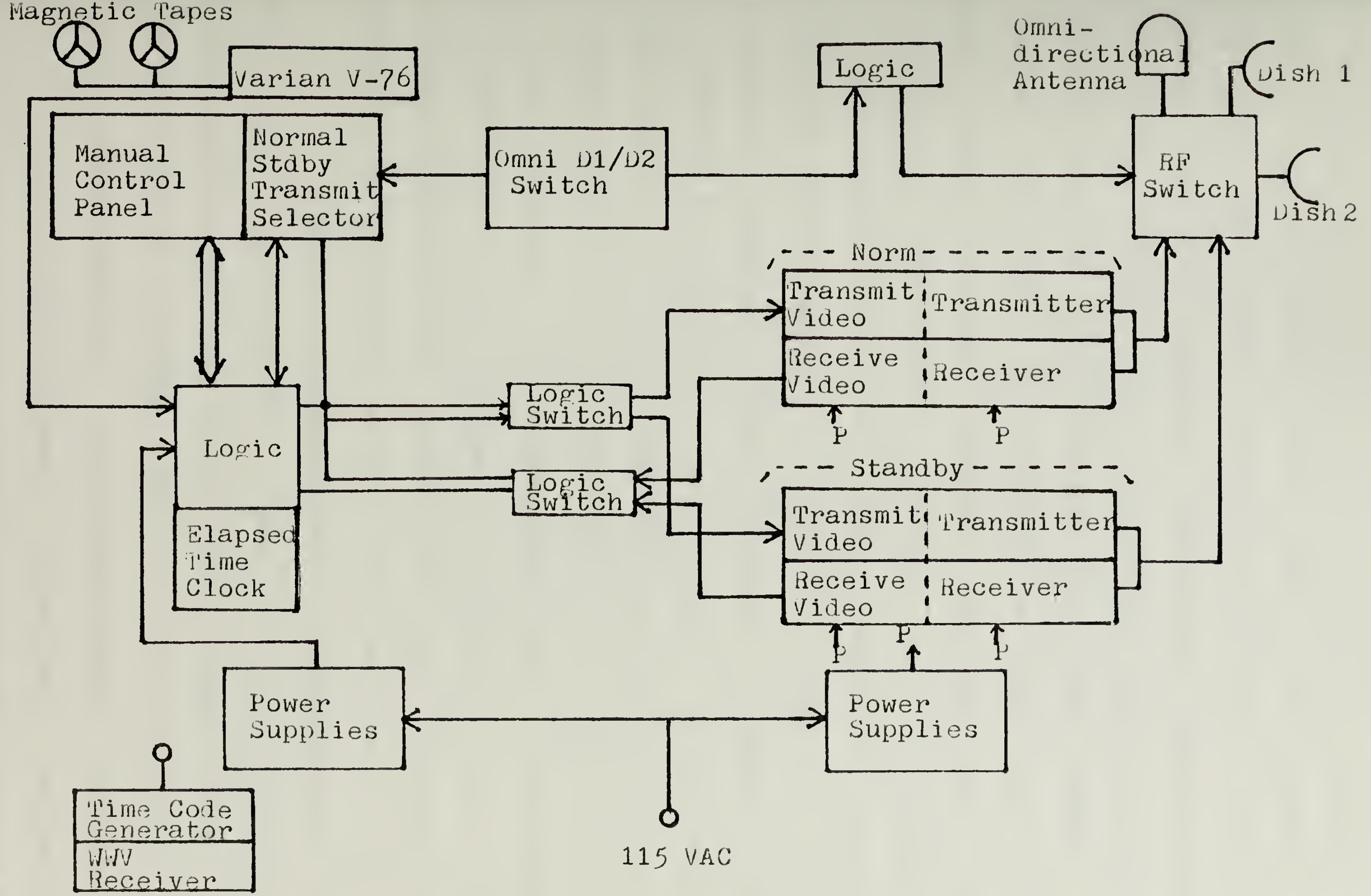

Fig. 21 C-Station Functional Block Diagram [Ref. 10]

solar power unit, omnidirectional antenna and associated logic. Fig. 22 depicts the functional block diagram of an A-Station. All requests from the C station are received through the T/R and routed to the receiver video circuitry. The receive video circuitry detects the presence of data on the upper and the lower sidebands of the two received channels, and applies this information in the form of discrete pulses to the logic section. The logic section checks the address of the desired A station. If it corresponds to its own stored address, the A station stores and acts on the remainder of the message. All different addresses are ignored. A properly recognized address causes the A station to store the message and act upon it in the digital storage and control logic section. The logic section then provides pulses to the transmit video section, which applied the proper modulation to the transmitter. The transmitter output is fed through the T/R switch to the antenna for transmission to a B unit. At the conclusion of the transmission, the A station automatically resets the T/R switch to the receive position.

Similar in appearance to A stations are D stations. They serve as relays between a group of A stations and the C station when there is no direct line-of-sight between the A stations and the C station. The D station consists of an RF receiver and transmitter, solar power supply, associated logic and an omnidirectional antenna. Unlike the A station, the D station's logic section does not act upon the received message.

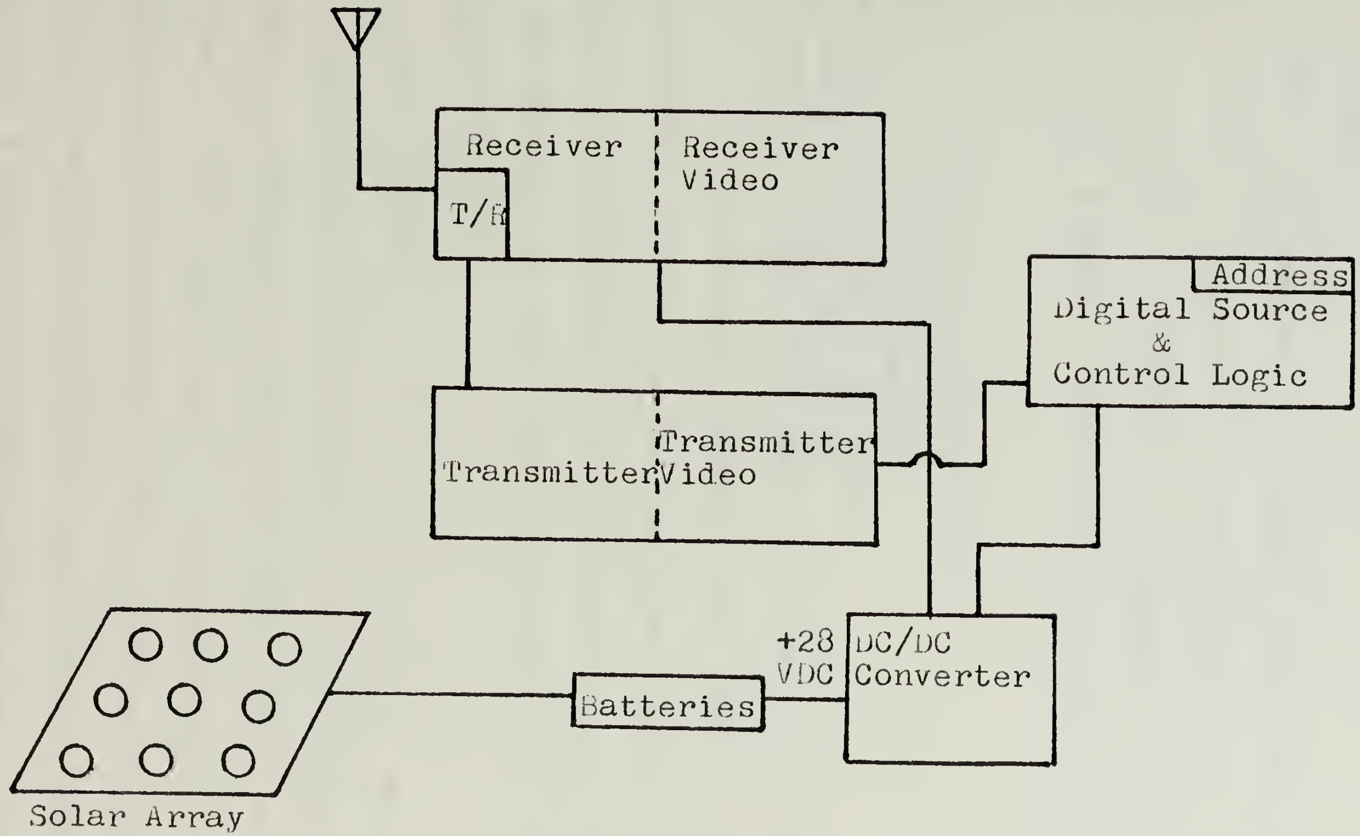

Fig. 22 A-Station Functional Block Diagram

The D station's function is only to act as a relay between A stations and the C station which are either not in direct line-of-sight or to extend the range of RMS coverage.

c. B Unit

The instrumentation package carried by the player (personnel, vehicle, aircraft) is referred to as a B unit. It is a microprocessor controlled transponder. The microprocessor used in the B unit is an 8085A with the following characteristics:

- 4 level priority interrupt control
- RAM 256 x 8 byte-expandable
- EPROM 5K x 8 byte-expandable
- Time tag resolution of 10 µsec
- 32 message storage capacity
- I/O feature 6 parts for input or output [Ref. 13]

Because of its microprocessor design, the B unit is very flexible in its ability to simulate various player types and in its capacity to enhance RMS. An example of this added capability is the ability to time tag events and store them during terrain induced dropout.

The function of the B unit is to act as a transponder to a range pulse sent from an A station (upon a command issued to that A station by the C station). Upon receiving a range request, the B unit waits a fixed period of time and then responds with a range reply. The transponder consists of a transmitter/receiver assembly, logic module, battery power supply and a variety of input/output accessories. Fig. 23 is a functional block diagram of a B unit. The major

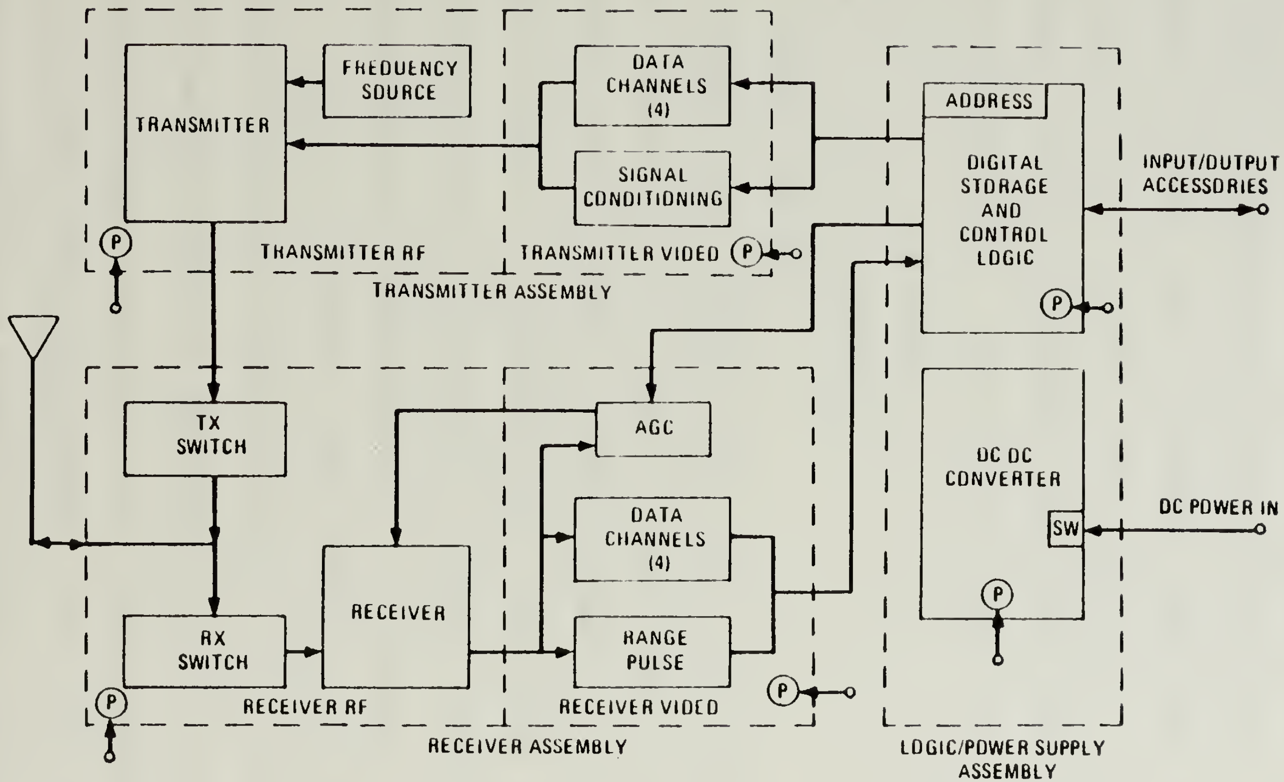

Fig. 23 B Unit Functional Block Diagram [Ref. 12]

components of the transmitter assembly are the crystal-controlled frequency source, the pulse amplifier, and the transmitter video. It is capable of a nominal peak power of 12 watts. The receiver assembly provides the functions of transmit/receive RF switching, filtering, amplitude detecting and automatic gain control (AGC). The logic/power supply assembly contains the microprocessor and associated logic and provides the required power. The size of the B unit is small (3.5 x 11.5 x 20.5 cm) and weighs only 1.3 kg. It requires 7.2 watts and is battery operated.

d. CDL and the MCS

Although the computer data link (CDL) and the Multi-Computer System are not actually components of the TCS, they do interface with the TCS and the ultimate performance of RMS depends on them. In the case that geography will not permit the control station (C station) and the facility that shelters the computation subsystem to be co-located, then there must be a means to transfer RMS information between the C-station and the Multi-computer system. At Fort Hunter Liggett this is accomplished by the CDL and its function is to link the two facilities to allow real time interchange of RMS commands and data during experiments. The CDL consists of two terminals each having a general purpose computer interface, microwave receiver/transmitter and associated antennas. Additional characteristics of the CDL are the following:

- Full-Duplex 7.770 & 7.870 GHz
- Bandwidth 20 MHz
- Data rate 230.4 kbits/sec
- BER 1×10^{-10}

The MCS is the facility which houses the computational subsystem. It is a complex of 15 computers operating concurrently performing real-time control, data collection, and processing for RMS and RTCA. Fig. 24 depicts the structure of the MCS in a recently conducted experiment.

The MCS is organized into four stems connected by a shared memory. Stem 1 interfaces with the C station via the CDL. It provides both communications and control functions for RMS and consists of three PDP-11/45s connected by 32 kbits of shared memory. Stem 2 consists of four PDP 11/45s connected by 32 kbits of shared memory and performs the position/location calculations for all players using Kalman filter routines. Stems 3 and 4 provide computational power to other required algorithms in RTCA and post-trial analysis. In this configuration, the MCS was able to accomodate in excess of 100 players while utilizing 127 A-stations.

B. CAPABILITIES

The first generation of RMS was deployed 10 years ago at Fort Hunter Liggett and has been in a state of constant change in an attempt to keep up with the present state of technology. The system has gained wide acceptance in the Department of Defense and has become a primary instrumentations system for several Joint Operational Test and Evaluations and other

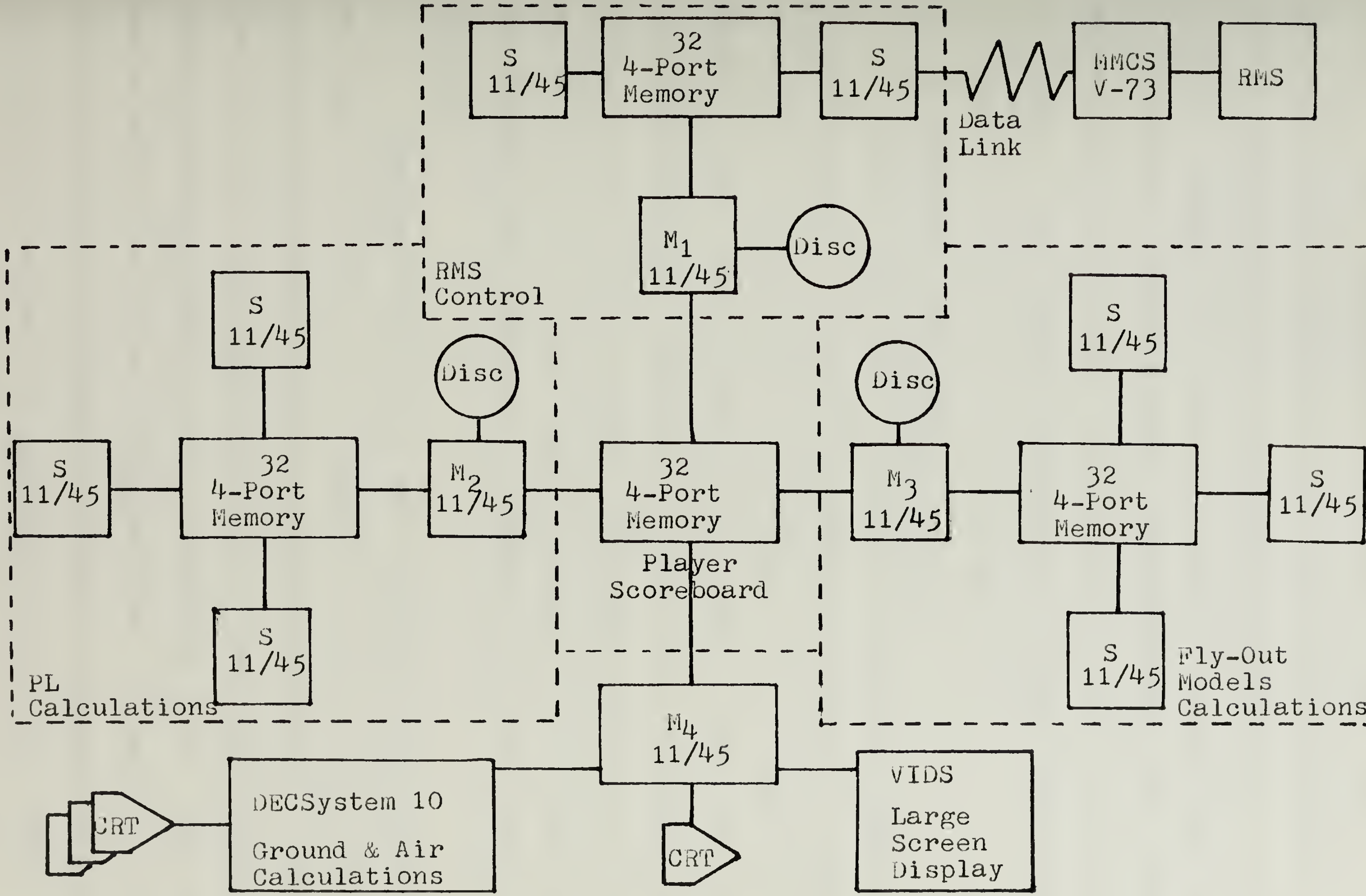

Fig. 24 Structure of MCS [Ref. 14]

Service tests. Throughout the history of RMS, static, dynamic and computer simulation tests have been performed to yield information on the performance characteristics of the system. Although they have been helpful in providing some information on the performance characteristics, the capability and accuracy of the RMS is not known precisely. In an attempt to classify the important parameters, several recent tests have been conducted and their findings follow.

1. Reported Accuracies of the RMS

Actual RMS position/location accuracy has been difficult to quantify. Tests have indicated accuracies ranging from 2 to 20 meters while the official stated figure is 5 meters in the x and y plane and an order of magnitude poorer for z [Ref. 15]. The figures represent the real-time performance of static or low dynamic players. The range resolution of the system is two meters and much more precise PL estimates can be obtained using statistical combinations during post-trial analysis.

Because there are so many variables which affect the accuracy of the RMS, it is helpful to look at the results reported from several tests conducted at different locations. The first test was conducted at the US Army Yuma Proving Ground, Arizona from June 1976 to February 1977. The test was a joint service test conducted under the general directions of the Under Secretary of Defense Research and Engineering, Director Defense Test and Evaluation (USDRE, DDTE).

The major objective of this test was to establish the accuracy of the RMS range instrumentation system. Table 13 gives the results of 197 trials during the ground static tracking test. In this test, B units were pre-positioned at surveyed ground points and the the RMS position data was recorded.

Table 13 Ground Static Tracking of B Units [Ref. 16]

	Trial	Error	Statistics
	x	y	z
68% of the trials (134) had RMS errors less than	1.8	2.0	55.2
95% of the trials (187) had RMS errors less than	5.1	5.1	147.6

NOTE: All numbers in meters

These figures do compare favorably with predicted values in all cases except the z coordinate. This larger error in the z coordinate was not attributable to some characteristics of the test, but is attributable to the near co-planarity of the A stations and B units. This problem is inherent in RMS and techniques to reduce the error will be discussed.

Table 14 Static RMS Accuracy Test Data [Ref. 17]

B-unit location	Systems Error			Standard Deviation		
Bench Mark	ΔX	ΔY	ΔZ	σ_x	σ_y	σ_z
E25	.3	3.6	-30.2	1.2	2.7	41.2
J27R	-2.0	-3.9	-23.1	2.9	4.1	63.5
E14R	-3.1	+3.1	-23.1	2.8	2.0	46.8
E27R	.8	3.2	28.3	2.3	5.1	193
E06	-6.8	-.9	18.5	1.6	.7	5.0
Bald Mountail	1.7	-3.0	-19.0	.09	1.6	9.6

NOTE: All numbers in meters

In a similar test conducted at Fort Hunter Liggett in May and June 1977, similar accuracies were reported for a static test. A summary of these results is found in Table 14.

The results in Table 14 also indicate that a 5 meter accuracy in the x and y coordinate can be expected. The z accuracy, as in the other test, is harder to predict. It is interesting to note the improved z error when the B unit was no longer co-planar with the A stations as in the above case when it was located on Bald Mountain.

The two tests performed at Yuma Proving Ground and Fort Hunter Liggett both generally support the published accuracy figures for the x and y direction for low dynamic players. It can be expected that RMS hardware which is

correctly adjusted and operationally ready, will report approximately a 5 meter error with a statistical measurement accuracy of less than a 2 meter standard deviation. Additionally, the tests indicated that comparable resolution could be expected in both static and dynamic situations. The z accuracy in both tests was found to be highly variable and very dependent upon the geometry of the RMS set-up. In the final report on the test conducted at Yuma Proving Ground, several recommendations were made to improve the z accuracy performance of RMS. These recommendations will be outlined in another section of this report.

As in most all tests, the results reported in the Yuma and Fort Hunter Liggett tests were under close to ideal conditions. Although the tests were designed to check the system under actual operating circumstances, they were not performed during the actual conduct of an experiment where many other factors would impact upon the accuracy of the system. The next section outlines the major causes of error and their impact on RMS accuracy.

2. Factors Which Influence the Accuracy of RMS

No test can accurately repreduce the operational environment of a system as well as the system operating in its functional environment. It is under these circumstances that equipment malfunctions occur, non-optimum system configurations are used, system elements are pushed to the maximum capability and environmental factors influence system

efficiency. Therefore in addition to parameters which can be easily varied for tests of RMS accuracy, the following areas are known to effect RMS accurcay, but have not been as deeply studied.

- Polling order and Geometry of A stations
- Earth Curvature and Atmospheric Effects
- Electronic Bias
- Z Accuracy
- MCS/MMCS Capacity
- Changing SNR and ENI

The following sections briefly explain the qualitative effects on accuracy of the above parameters.

a. Polling Order and Geometry of A Stations

One of the chief limitations of the RMS is its sequential transmission design, where only one station can be transmitting at a time. This requires a polling technique which is controlled by the MMCS in RMS. It provides for selectable polling rates of 10/sec, 5/sec, 1/sec, (1/2)/sec and (1/4)/sec with the highest being assigned to the fastest players while the slower rates are assigned to slower players.

The first polling scheme used in RMS was clumped polling. An example of clumped polling is during a one second period, six to ten ranges are gathered on a player by an A station in a six to ten msec period and then the position is updated. A better polling technique which has been used recently is uniform polling. In uniform polling, the range

data is obtained uniformily over the entire polling interval, e.g. 1 sec in the above example. This technique has provided an increase in PL data quality.

In addition to the polling technique used, the MMCS also controls the selection of the geometry of A stations to be used to determine PL data on a player. The best PL data is obtained if the A-B-A angle for successive pollings is near 90°. One algorithm which has been used selects A stations on the basis of response and then selects those that give the best geometric relationship for calculating the PL of the player. Proper geometry is essential for minimum error and thus the algorithm used in the MMCS can greatly affect PL accuracy.

b. A Station Location and Electronic Bias

Included in the preparation for an experiment which uses RMS, coverage tests are conducted to determine the optimum placement and density of A stations. This procedure is done to ascertain the degree with which RMS can communicate with each player and the best location for each A station for optimum coverage. To facilitate this procedure, software routines have been developed to analyze raw range data and give several visual and other analytic tools to study the best A station placement for optimum coverage. Because RMS determines the position of a player by multilateration from known positions (A stations), the location of the A stations should

be known to a high degree of accuracy. Past experience has demonstrated that A station location errors of up to $\pm$ 10 m have occurred [Ref. 18].

Another source of error in RMS which must be accounted for is electronic delays in instrumentation components. These errors which are equally as serious as A station location errors are more common and hard to eliminate. The electronic equipment used in both the A stations and B units is carefully adjusted, and measurements of signal delays in each piece of equipment are made before the conduct of an experiment. These procedures help to eliminate the errors caused by delays (bias) but temperature variations and component aging still contribute to bias errors of up to $\pm$ 10 m in some instances.

c. Earth Curvature and Atmospheric Refraction

If the PL routine used in RMS assumes a flat earth, small errors in the z component of position are introduced at long ranges. Fig. 25 illustrates the effect.

A first order approximation for this error is

$$e = \frac{r^2(\text{km})}{12740\text{km}} \quad \text{assuming } r^2 \gg e^2 \qquad \text{[Ref. 19]}$$

The signifance of this error is only important for long ranges as shown in Fig. 26. It should be noted that the magnitude of the error introduced by assuming a flat earth, even at long ranges (r>10 km) is insignificant to the error with which RMS can predict the z component of a players

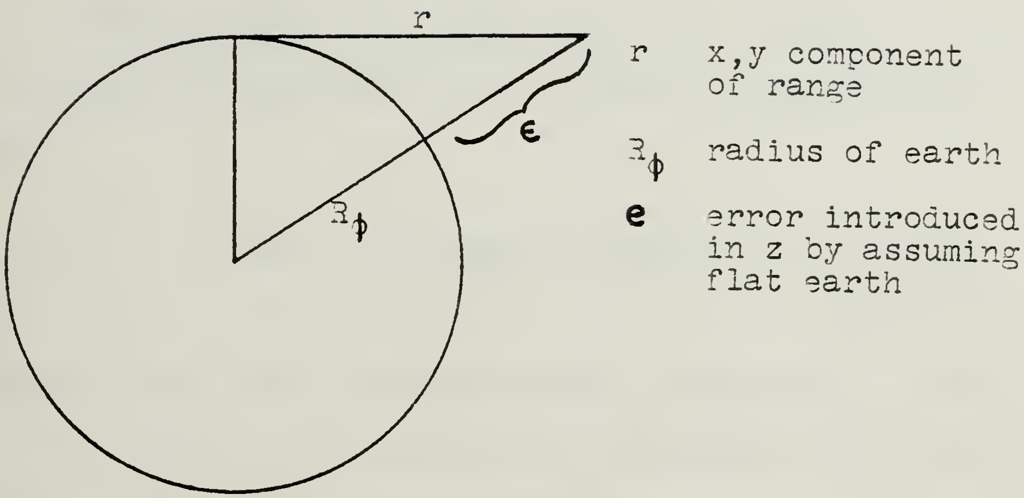

Fig. 25 Effect of Earth Curvature

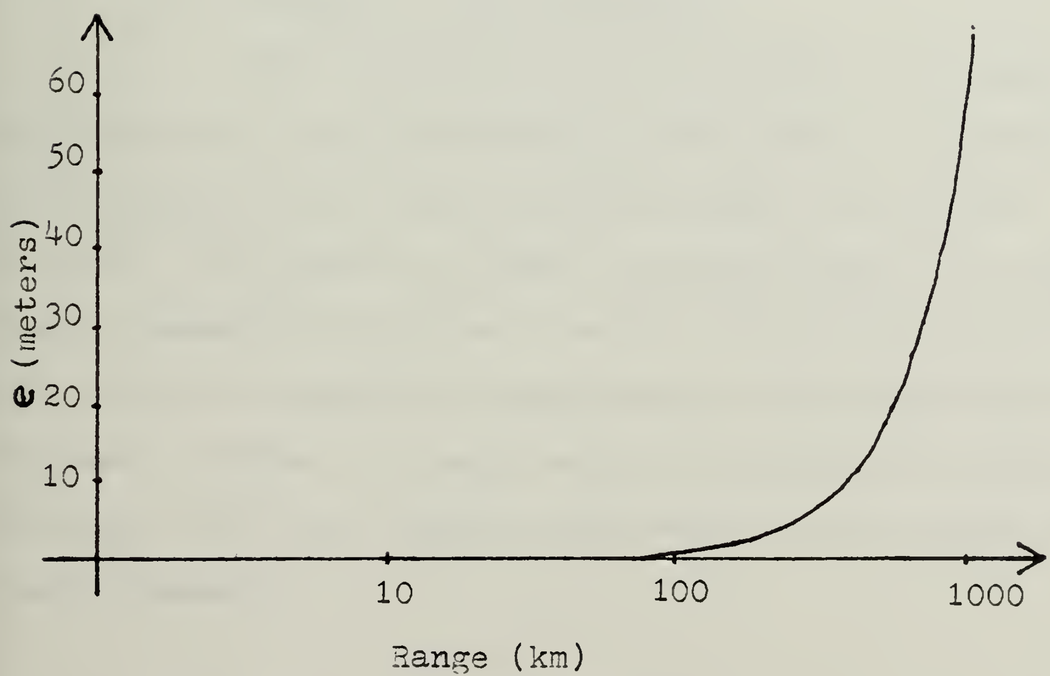

Fig. 26 Error in Z by Assuming Flat Earth [Ref. 20]

position. It is for this reason that the current PL routine used in RMS assumes a flat earth.

The velocity of a radio wave is a function of the medium in which it propagates and is given by the following expression:

$$V = c/N \qquad \text{where } c = \text{speed of light} \ \& \ N = \text{index of refraction}$$

The parameter N must be included because the medium is not a vacuum. The index of refraction is a function of the medium's temperature, water vapor pressure and air pressure. Experimentally it has been determined that corrections for atmospheric refraction must be made for ranges exceeding 3 km where the error is approximately 1 meter.

d. MCS/MMCS Limited Capacity

The limitation imposed by RMS on the number of players used in an experiment is the number of commands (range and communication) that the MCC and MMCS can process. Theoretically, the capacity of RMS is approximately 1275 equivalent range commands, and it has been determined that practically the system is capable of approximately 1000 equivalent range commands. Below is a table which reflects data collected during a trial in a recent experiment on the allocation of RMS range commands.

Table 15 Allocation of RMS Range Commands on MCS [Ref. 21]

Player Type	No.	Polling/sec	Total	Percentage of MCC
Fixed Wing	4			28.3%
-ARPIS Pod	8	30	240	
SCORE	4	10	40	
Rotary Wing	9	30	270	27.3%
Airborne A	1	40	40	4%
Ground Players	100	4	400	40.4%
Total Players plus Airborne A	113		990	

It should be recognized that fixed wing players require far higher polling rates than ground players and that this non-equivalence of player types in allocating RMS commands puts certain restraints in player types and numbers that RMS can handle in a particular experiment. Currently, the capacity of the MCS exceeds the MMCS data transmission rate capability.

e. Changing Signal to Noise Ratio and Electromagnetic Interference

Another factor which has been found to seriously degrade RMS PL performance is changing signal strengths at both the A stations and B units. Errors as much as 2.5 meters have been found for signal level changes from -67 dbm to -23 dbm. There are many causes for changing signal to noise ratios (SNR), but the most predominate ones found in RMS at

Fort Hunter Liggett are the following:

- Multipath
- Antenna Patterns
- Terrain Shadowing and Coverage Limits
- Interfering Signals

Another problem which degrades RMS PL performance is radio frequency (RF) interference. This seems particularly true for B units. Field testing has revealed that B units might be susceptible to interference from other RF equipment used in adjoining field experiments.

f. z Accuracy

One of the major deficiencies of RMS is its inability to determine accurately a player's position in the z coordinate (altitude). Generally, RMS is capable of determining a player's position in the x and y coordinate an order of magnitude more accurately than can be expected in z. Although this is an optimistic conclusion about z accuracy, it has been supported by experimental data. It is not a surprising result because of the near co-planarity of the A stations and B units at Fort Hunter Liggett.

In a typical application of RMS at Fort Hunter Liggett, the angle subtended by the A station from the B unit in the vertical direction is a few degrees. Fig. 27 is a computer simulation showing the results of 10,000 determinations in the x-z plane. The horizontal axis represents the angle subtended in the z coordinate by the A stations at the

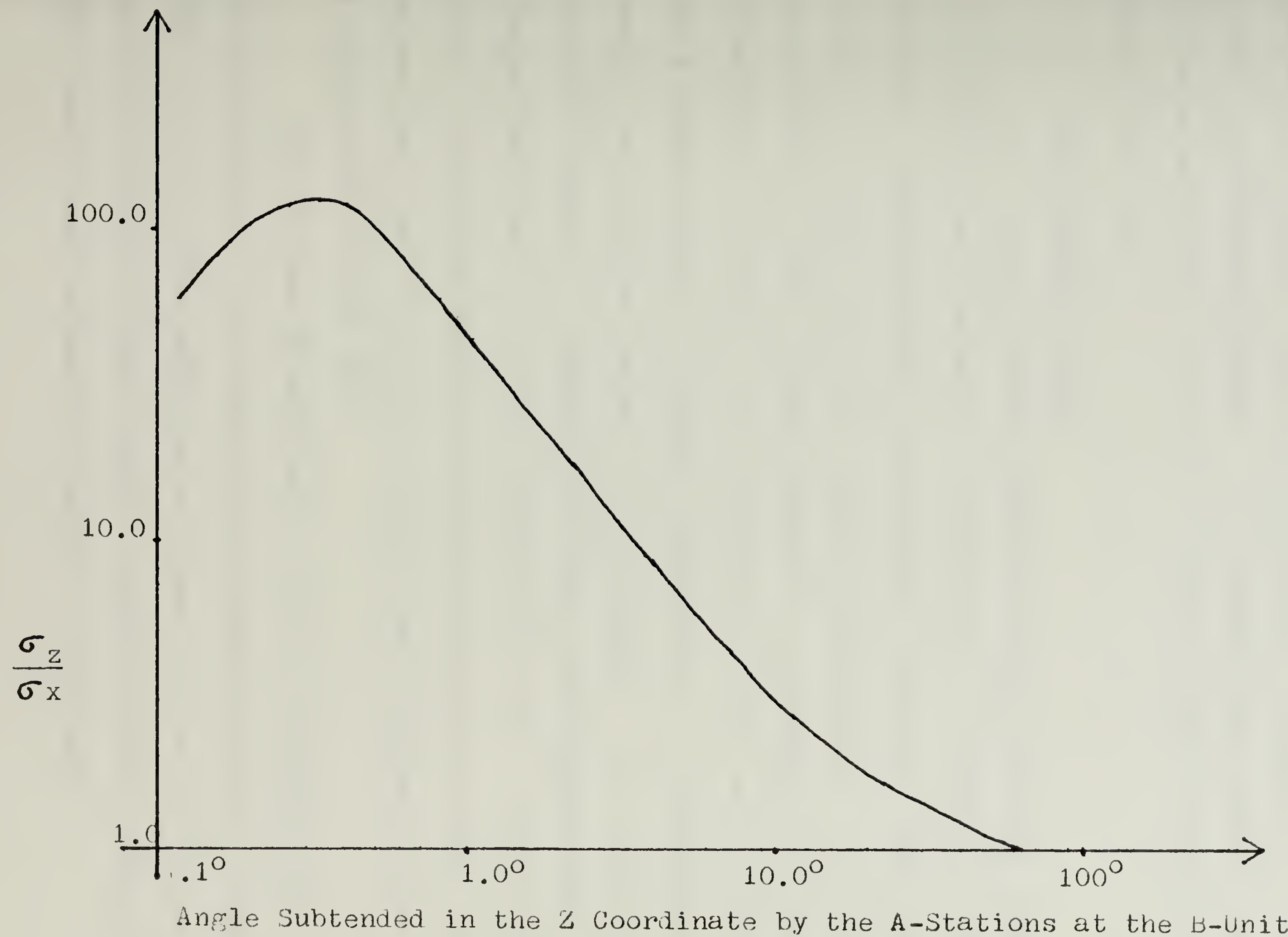

Fig. 27 Results of Computer Simulated Determinations [Ref. 22]

B unit while the vertical axis is the ratio of the z coordinate error's standard deviation to the x coordinate error standard deviation. This ratio provides a comparison of the x and z coordinate accuracy. It confirms that the best that can be expected in z accuracy is about an order of magnitude worse than x or y.

3. Improvements to RMS

All of the problems mentioned above have been studied and progress has been made in eliminating or reducing their effects. Uniform polling has improved the quality and reliability of PL data over the clump polling method. Also, new algorithms are being tested and used in selecting the best geometry of A stations. As the need grows for more variety and a larger number of players, methods must be developed to handle the increased number of RMS commands. One study indicated the choice of command mix (range and communication) could change the capacity of the system by over 30%. In the same study it was found that an increase in capacity of 50% could be realized when D stations (relays) were eliminated from the A station array [Ref. 23].

The problem of multipath, terrain shadowing and changing SNRs will be helped by an improved antenna design. The use of circular polarized antennas in lieu of vertically polarized antennas should improve communications between all RMS elements and improve the quality of RMS data.

A remaining unsolved problem is the accuracy of RMS in the z component. In the TAVSAL experiment, use of an airborne A station theoretically eliminated the near co-planarity of the A stations and the B units. The resulting altitude data while using the airborne A station did not significantly improve the quality of z data.

APPENDIX B
ARCHITECTURE OF GLOBAL POSITIONING SYSTEM

A. SPACE SEGMENT

The early Navigation Technology Satellites (NTS) of Phase I and the Operational Navigation Satellites (ONS) of Phase II are both three-axis stabilized spacecraft. This permits the satellite's antennas to point towards the earth while gathering sun's energy with solar arrays. The spacecraft to date, March 1981, have been built by the Space Division of Rockwell International. The design lifetime for the operational satellites is 5 to 7 1/2 years. The six deployed satellites used during Phase I testing were launched from Vandenburg Air Force Base, California with a modified Atlas booster with an Agena upper stage. Phase II satellites will also be launched by conventional boosters until the space shuttle becomes operational in 1981-82. A major advantage of the space shuttle will be its multiple deployment ability, up to six satellites at one time.

Current Phase II and III plans are for an 18 satellite system with the possibility of increasing the number of satellites to 24 in the future. Fig. 28 illustrates the deployment of a typical 24 satellite system. There are three orbital planes each inclined by 63° with respect to the equatorial plane and offset from one another by 120° in longitude. Six or eight satellites are equally spaced in circular orbits

with periods slightly less than 12 hours. The orbital parameters are based on the sidereal day which is 4 minutes and 3.4 seconds shorter than a solar day. Therefore, each satellite will arrive at the same point above the earth 4 minutes and 3.4 seconds earlier each day [Ref. 24]. Also because of the earth's rotation, there will be a different ground track for each of the satellites within a given orbital plane.

A constellation of 18 satellites provides for a minimum of four and a maximum of nine satellites always visible (greater than 5° above the horizon) at the equator where maximum satellite separation occurs. A 24 satellite constellation provides a minimum of six visible satellites and a maximum of eleven. The required angle above the horizon that a receiver requires the satellites to be before signal strength is considered adequate also influences the number of visible satellites. Fig. 29 is a histogram of the probability of satellite availability for two cases, e.g. 5° and 10° elevation angles. This histogram was based on a 24 satellite constellation. Note, four satellites are required for the computation of three dimensional position data. The satellites are placed into as near circular orbits as possible but several external forces cause perturbations in their orbits causing them to deviate from true Keplarian orbits. It is because of these perturbations that ephemeris corrections

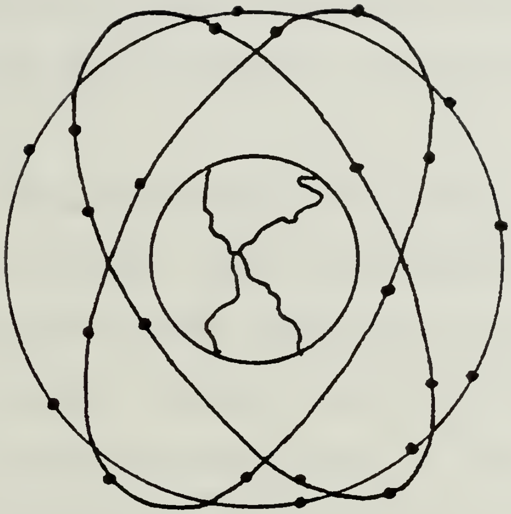

Fig. 28 GPS Orbital Configuration, 24 Satellites

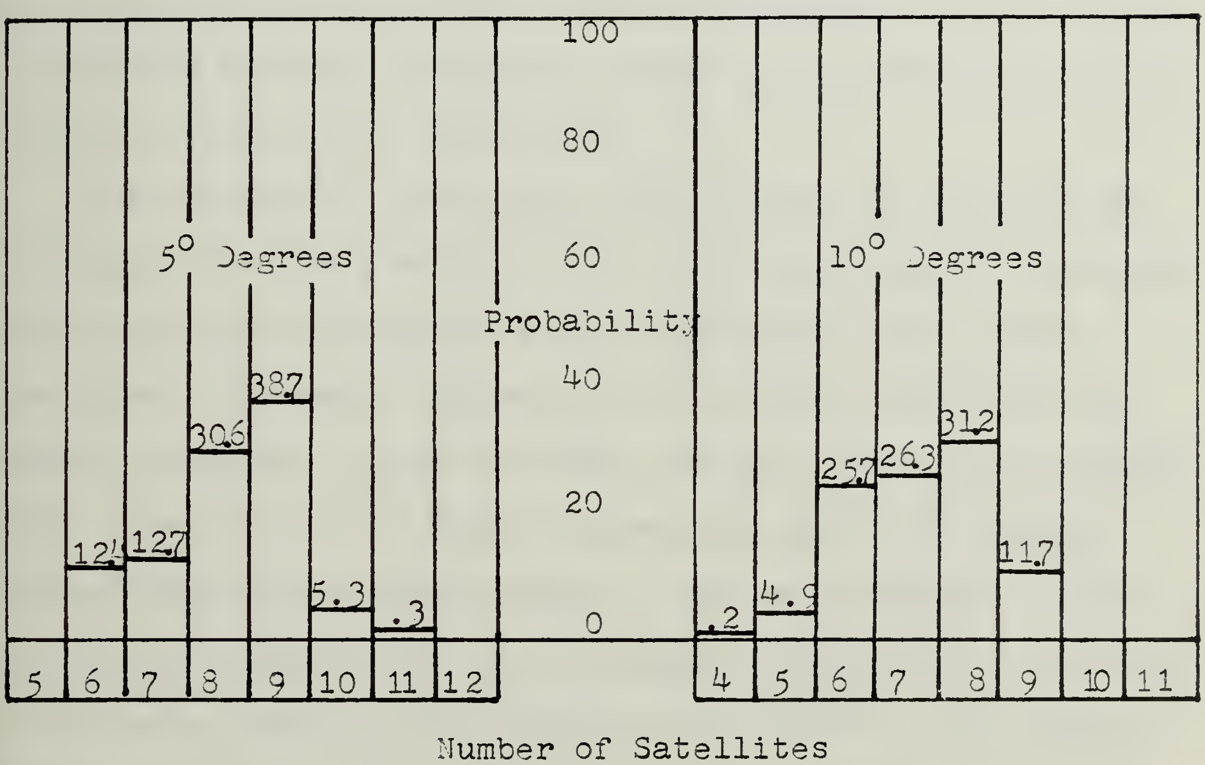

Fig. 29 Satellite Availability Histogram [Ref. 25]

are necessary to accurately predict the satellite location required in the user's position calculation. The dominate effects on the orbit of the satellites are the earth mass attraction, the second zonal harmonic, lunar gravity and solar gravity.

The Operational Navigation Satellites (ONS) planned for Phase II and III will contain five major subsystems. The electrical power subsystem (EPS) generates the necessary power for all other systems on the satellite through two solar arrays. The EPS also stores power in three NiCd batteries which serves as the backup power supply in the event of a solar outage. Regulation of the main power bus, controlling the power distribution and positioning of the solar arrays for maximum sun angle incidence are also functions of the electrical power subsystem.

The navigation subsystem is the primary payload of the satellite and its function is to store and transmit the navigation message necessary in the calculation of a user's position. The basic components are a highly accurate frequency standard, a pseudo-random signal generator, a computer, data formatter, two L-band transmitters and a 12 element shaped-beam helix antenna array. The key component of the navigation subsystem is the frequency standard from which all frequencies used in the satellite are derived. The nominal frequency of the satellite clock is 10.23 MHz but this is slightly offset to a center frequency of 10.229999999999 MHz

to allow for relativity effects. During Phase I, the first three satellites launched (NTS-1, 2 and 3) contained three rubidium frequency standards as well as a crystal controlled oscillator. NTS-4 was the first satellite launched that carried an additional cesium standard but the clock failed once in orbit. The stability and accuracy of the satellite frequency standard is critical to the position accuracy obtainable by the user. The ground control segment monitors the satellites frequency standard daily (with reference to GPS time) and generates clock correction parameters for transmission to the satellites. They are then re-transmitted to the user with navigation signals where they are used to determine the precise magnitude of the satellite's clock offset.

The function of the Telemetry/Tracking and Commanding (TT & C) subsystem is to provide satellite state-of-health telemetry downlink, tracking signals, command uplink and navigation capabilities to support the satellite operation. The associated antennas with the TT & C are forward and aft conical spiral and biconical horn antennas. They are connected to the Air Force Satellite Control Facility Standard Space Ground Link (SGLS) S-Band receivers for uplink data and S-band transmitters for downlink data.

The final two subsystems are the Attitude and Thermal Control Subsystems, ACS and TCS respectively. The primary function of the ACS is to maintain proper attitude for correct antenna pointing and solar array positioning. Attitude

control is provided by control electronics, reaction wheels, earth and sun sensors, and a system of small thrusters. The thermal control subsystem monitors temperature throughout the satellite as well as maintains proper temperature through passive and active control devices. Proper temperature is maintained in the navigation subsystem by heat-rejecting surfaces (e.g. temperature sensitive, louvered radiators) and proper satellite attitude. Temperature control is maintained in the battery compartment and ACS through the use of strip heaters.

In Phase I, a total of six satellites were launched and all except one is currently operational.

B. GROUND CONTROL SEGMENT

The ground control segment of the GPS program has as its primary function the generation of precise navigation data for the user. It does this by tracking the satellites, transmitting data to the satellites, analyzing data received from the satellites and managing the entire constellation. The ground control segment consists of a central continental United States control center, several monitor stations, a satellite upload station and several other supporting facilities.

During Phase I, there were four monitoring stations located at Elmendorf AFB, Alaska; Guam; Hawaii; and Vandenburg AFB, California. These are unmanned tracking stations which are under the direct control of the Master Control Station (MCS).

1. Monitor Station

The equipment at a Monitor Station (MS) consists of multiple antennas, a multichannel receiver, a cesium frequency standard, a computer processor and environmental data sensors. The tracking function is accomplished through the satellite's receipt and re-transmission of a 500 kHz pseudo-random noise (PRN) signal. The ranging data is used to determine the satellite ephemeris. The multichannel receiver measures the pseudo-ranges and delta pseudo-ranges (integrated doppler) with respect to the cesium frequency standard which is synchronized with GPS time. Additionally, the receiver detects the data on the navigation signal. The environmental sensors collect local meteorological data which is used for signal path delay corrections which are made to the monitoring station's tracking data. The computer processor controls all the data collection at the MS and it provides the data interface with the Master Control Station. All of the data from each MS is routed to the Naval Surface Weapons Center (NSWC) via the Master Control Station where ephemeris and clock correction parameters are generated for each satellite. Plans call for up to eight monitoring stations in the fully deployed system.

2. Master Control Station

The Master Control Station is located at Vandenburg Air Force Base. Its purpose is to completely control the operation of the control segment and the space segment. The

MCS performs the computations necessary to determine the satellite's ephemeris and clock correction parameters, generates the satellite's upload of user navigation data, maintains a record of the satellite's navigation processor contents and status and provides an interface between the Satellite Control Facility (SCF) and the NSWC.

The SCF located in Sunnyvale, California is part of the Air Force satellite control system which performs tracking, telemetry and commanding functions over all Department of Defense spacecraft. Its function in supporting the GPS program is several fold. It provides the necessary support to assess the state-of-the-health status (SOH) of each satellite and it determines critical orbital events and recommends corrective actions for satellite anomalies. Remote tracking stations (RTS) assist the SCF in accomplishing tracking, telemetry and commanding functions as the satellite constellation requires. In addition to its other functions, the SCF also provides backup upload capability in the case of an upload station failure. The NSWC also provides support for the MCS by providing a predicted reference ephemeris from data gathered by the monitor stations. The predicted reference ephemeris is generated once a month from pseudo-range measurements and is forwarded to the MCS for use in the ephemeris estimation process.

The MCS calculates the actual ephemeris error model which is uploaded to the satellites as part of the navigation

message. The satellite's ephemeris model which is used to describe the satellite's actual orbit is characterized by a set of six Keplerian orbital parameters which describe the satellite's ephemeris for the interval of time the parameters are transmitted. Three fix the orbital plane relative to the earth and the other three define the orbit. In calculating the ephemeris parameters, the MCS uses data collected by the monitoring stations and tracking data accumulated over a long period of time. The ephemeris determination technique used is a two step process. First, an off-line, least-squares batch fit is made using approximately one week of measurement data. Second, a first-order correction is computed on-line by a Kalman estimator [Ref. 26]. The MCS progressively refines the information defining the gravitational field, solar pressure and signal delay characteristics of the MS before arriving at the ephemeris parameters which are uploaded to the satellites.

GPS system time is maintained at the MCS through the use of highly accurate cesium beam standards. The monitoring stations which also have cesium beam frequency standards are kept in synchronization with GPS time by the MCS. An additional function of the monitoring station is to continuously collect data on the stability and accuracy of the satellite's atomic frequency standard. This data is passed on to the MCS where clock correction parameters are calculated. These

clock correction parameters are included in the navigation message which is uploaded once per day for relay down to each user as part of the satellite's data stream.

3. Upload Station

The GPS upload station (ULS) is located at Vandenburg Air Force Base, California where it provides the interface between the MCS and the satellites. It utilizes an S-band command and control uplink to daily upload data into a satellite's navigation processor. In addition to uploading data, the ULS can request processor diagnositics commands to adjust the phase and frequency of the satellite's clock and major orbital corrections.

There are two modes which the ULS can use to upload the daily navigation message. The primary mode routes the data by the TT & C to the receiver/demodulator, signal conditioning unit's decryption unit and then to the navigation computer for storage. In the alternate mode, data is routed via the encrypted or by-pass TT & C path in the command format prior to being stored in the navigation processor. The uplink is accomplished at a 1 kBPS rate for the daily navigation message and a 64 BPS rate for command messages. There are a total of 26 one hour pages that are uploaded daily to each satellite. The two additional pages provide overlap should satellite contact be delayed. To insure correct upload, the ULS verifies each block of data prior to the next block

being transmitted. The Air Force Satellite Control Facility (SCF) provides back-up for the upload station at Vandenburg AFB.

C. USER SEGMENT

In March 1977, the Phase I testing of user equipment began. The equipment represented three contractors selected to produce prototype GPS receivers to undergo Phase I testing at the Army's Yuma Proving Ground, Arizona. The user equipment ranged from relatively simple and light weight manpack-type receivers to sophisticated receiver/processors designed for accurate performance in high-dynamic environments such as encountered in fighter aircraft and missiles. Future plans are to include a GPS navigation system on the space shuttle. This will require special adaptions to user equipment to meet the special requirements and rigors of manned or unmanned space flight application.

The Phase I user equipment can be broken down into three main categories depending upon the dynamics of the host vehicle, low dynamic, medium dynamic and high dynamic. Table 16 is a summary of the user equipment and its characteristics which underwent testing during Phase I. At the conclusion of Phase I testing, two contractors, Magnavox and Collins/Rockwell, were chosen to manufacture user equipment for Phase II testing. User segment activities during Phase II will concentrate on the design, development, manufacture and test

Table 16 User Equipment Summary

Set	Number of Channels	Dynamic Range	Operating Frequency		Signal Code		UE Contractor
			L_1 1575MHz	L_2 1227MHz	P	C/A	
XU	4	High	X	X	X	X	Magnavox
YU	1	Medium	X	X	X	X	Magnavox
XA	4	High	X	X	X	X	Magnavox
YA	1	Medium	X	X	X	X	Magnavox
HDUE	5	High	X	X	X	X	Texas Inst
MVUE	1	Low	X	X	X	X	Texas Inst
AFAL/GDM	5	High	X	X	X	X	Collins/Rockwell
MP	1	Low	X	X	X	X	Magnavox
Z	1	Low	X			X	Magnzvox

of GPS production user equipment. This generation of user equipment will be designed to operate in 30 different host vehicles and be integrated into the navigation or fire control systems of the eight host vehicles listed in Table 17.

Table 17 Phase II Host Vehicles

- Main Battletank (M60/XM1)
- Helicopter (UHGO)
- Attack Aircraft (A6E)
- Fighter Aircraft (FI6A)
- Maritime Aircraft (P3C)
- Bomber Aircraft (B52D)
- Aircraft Carrier (CV64)
- Submarine (SSN)

D. ARCHITECTURE OF GPS RECEIVER

The GPS signal transmitted by each satellite is a spread spectrum signal which employs a PRN modulation structure. This modulation technique provides the necessary precise timing marks required to calculate the pseudo-ranges; it provides separation of the various satellite signals; and it provides a processing advantage against multipath and jamming signals. All GPS user equipment must be capable of certain functions.

They include the selection of the "best" constellation of four satellites from those available. The receiver must be able to acquire, track and demodulate satellite signals even under high dynamic conditions. Finally, the user equipment must contain the capability to compute the user's position using the demodulated data and the measurements of pseudo-range. The principal components used in GPS user equipment to perform these functions are the antenna, the receiver, the navigation computer and various input/output (I/O) devices. Depicted in Fig. 30 is a general block diagram of a typical GPS receiver and its functions.

The antenna is one of two general types. In non-hostile environments, the antenna is a relatively simple element providing approximate isotropic gain from zenith to horizon at one or both of the GPS frequencies. This is referred to as a fixed reception pattern antenna, and because the signals are right-hand (RH) circularly polarized a conical spiral antenna is employed. In high jamming environments, a null steering antenna is employed. This type of antenna has a controlled reception pattern and is more complex than the fixed pattern antenna. It usually requires additional antenna control electronics.

GPS receivers are processor controlled. The functions of carrier tracking, loop-filtering, data detection and time-of-arrival measurements are all performed in the receiver but under the control of the processor. In addition to controlling

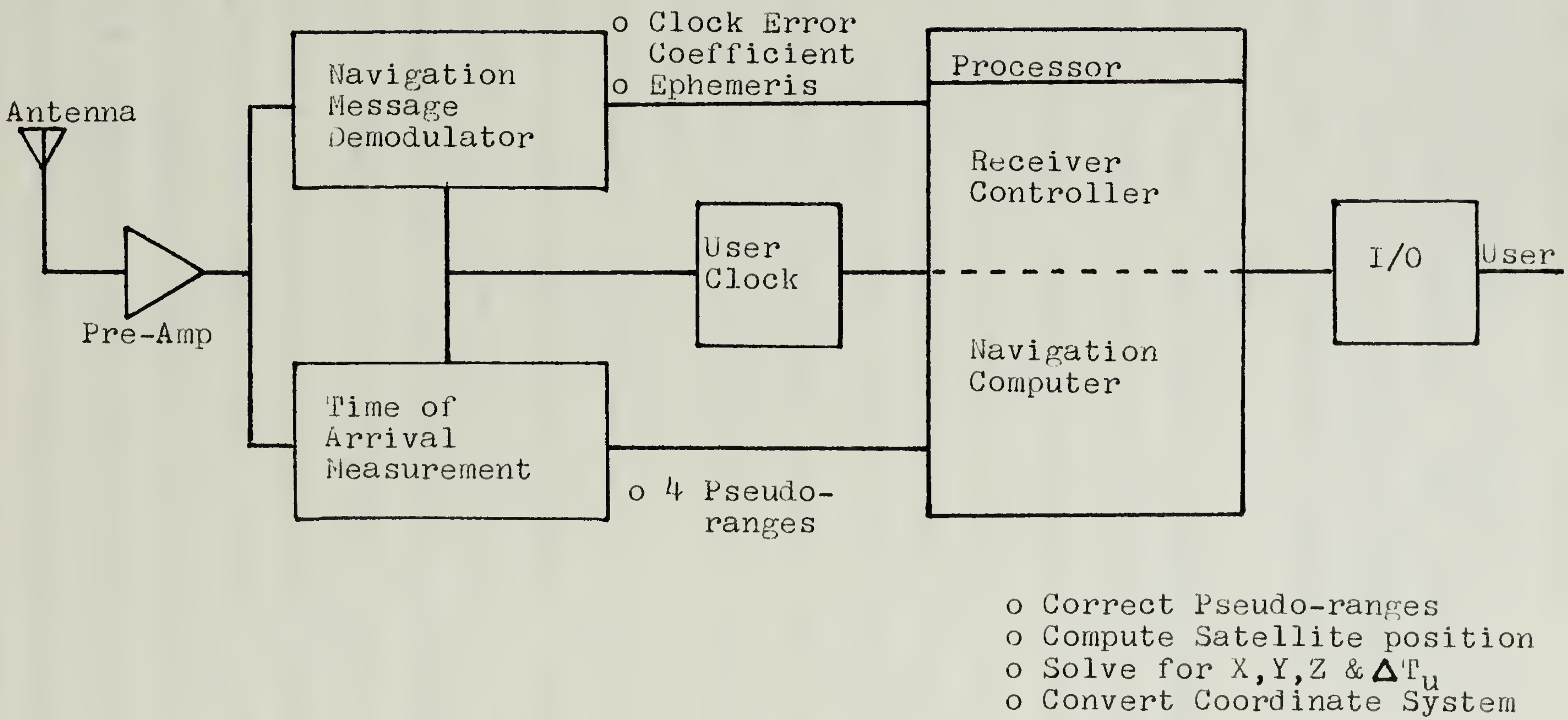

Fig. 30 General Block Diagram of GPS Receiver

the receiver, the processor selects the satellites to be used and corrects the pseudo-ranges for propagation effects used in the computation of user position. The output of the navigation processor is in the form of user position in Cartesian ECEF coordinates, but is is capable of converting to several other common coordinate systems.

The interface between the receiver and the operator is one of a set of I/O devices which are as varied as the applications of GPS. They are usually microprocessor controlled and can be as simple as an alphanumeric keyboard and LED display or they can be complicated and drive a pilot steering display (PSD). Generally, the I/O also accomodates the use of a digital message device (DMD) which can be used to pass positional information over a radio link or to externally initialize the receiver.

The minimum GPS receiver provides only a single channel capable of receiving one satellite at a time. To obtain the required four pseudo-ranges necessary to calculate a user's position, the receiver must sequentially step through the four "best" satellites. More elaborate receivers contain as many as five channels and are capable of processing the five signals simultaneously. The elaborateness of the receiver structure is primarily dependent upon the maneuverability of the host vehicle and secondarily upon the accuracy and interference resistance required. Man and vehicular transportable sets usually require only single channel receivers whereas high

dynamic aircraft such as fighter aircraft, usually require the multichannel receivers.

In high-dynamics host vehicles, the GPS user equipment is usually connected to an Inertial Measurement Unit (IMU). The IMU helps maintain navigation accuracy by augmenting the GPS receiver with additional information during high acceleration maneuvers. The IMU also helps the receiver in satellite carrier signal tracking by supplying information about the effects of user motion on the carrier frequency (Doppler). GPS user equipment is referred to as aided when used with an IMU. The determination of velocity by the GPS receiver also uses information supplied by the IMU. Velocity estimates are made by measuring the Doppler shift in the carrier frequency of the navigation signal from the satellites. These measurements are called pseudo-delta range measurements. They are combined with pseudo-range measurements and outputs from the IMU and are the inputs to a Kalman filter which estimates user velocity. The IMU data supplied to the Kalman filter provides superior smoothing and less noisy navigation solutions. Outputs of the Kalman filter include position, velocity, acceleration, clock bias and clock drift rate.

All GPS receivers require a procedure for the operator to follow and certain information to facilitate start-up. The frequency standard in user equipment is a high quality, temperature controlled quartz crystal oscillator. Before operation can begin, the oscillator must be brought up to nominal

temperature. The operator must also provide the receiver with information pertaining to the approximate satellite position, approximate user's position and time. Various methods of introducing this data are available. Examples of methods used with Phase I equipment include keyboards, cassettes, radio links or a data bus from another GPS receiver.

For the purpose of satellite selection and acquisition, the information regarding user's position, satellite position and time need only be accurate to a few kilometers and minutes, respectively. The collective information on all the satellite's position is called the almanac and is transmitted as part of the navigation data message. This allows users to periodically update their stored almanac. More information on the almanac and navigation data message are presented later in this appendix. There are two methods an operator may use during a cold start-up of a receiver. The first is the easiest and quickest. An almanac may be transferred from another active GPS receiver. This can be done by several of the means mentioned above. An alternate method is a search-the-sky procedure. The receiver tries to acquire the Coarse/Acquisition signal from a satellite without a prior knowledge of the satellite's visibility or Doppler shift. Once the receiver has acquired a satellite signal, it can then collect the almanac on all other satellites but the signal acquisition process may take many minutes.

Once the approximate user position, time and a valid almanac are known by a receiver, the navigation processor can

execute a satellite selection algorithm. Current satellite selection algorithms consider some or all of the following parameters. The best constellation of four satellites occurs when one satellite is at the user's zenith and the others are low on the horizon with the greatest angular separation. This is the optimum geometry for navigation calculations and a discussion in a later section will address how the quality of the geometry is estimated. Satellites which will soon set (less than 5° or 10° above horizon) also are considered in the satellite selection process. Finally, satellite health and signal quality may be considered. Subsequent selection should be reviewed every few minutes to minimize navigation error. On most Phase I user equipment this automatically occured.

A more detailed description of the user equipment used in the demonstration conducted at Fort Hunter Liggett is contained in Section IV.

E. THE SIGNAL--TWO FREQUENCIES

In selecting the frequencies and the modulation scheme used in the GPS program, several important signal properties were considered very desirable. They included the following. The modulation technique had to allow for accurate time measurements without ambiguity, i.e. σ_t<10 μsec. Also the modulation technique should provide for a highly accurate "protected" signal along with a simpler signal which provided lower accuracy and was easily acquired in a short time (approximately 1 or 2

minutes) by the receiver. Additionally, the modulation technique had to exhibit good multiple access properties. The receiver would typically receive simultaneous transmissions from 4 - 11 satellites. The technique also had to be resistant to interference from low-power narrowband interference as well as moderate power intentional interference. Plus, it had to reject or greatly reduce multipath interference where differential multipath delay were 200 nsec or greater. The choice of frequency had to allow for accurate doppler shift measurements for use in determining user velocity, i.e. less than 0.1 Hz. Ionospheric delay predictions required the use of dual frequencies with a separation greater than 20% to accurately measure ionospheric group delay [Ref. 27].

1. L_1 and L_2 Characteristics

In order to provide the precise time marks, to separate the various satellite signals and to obtain processing advantage against multipath and jamming signals, GPS uses a spread spectrum modulation technique. It employs a PRN modulation structure on two L-band carriers. The L-band center frequency selection had the advantage over lower frequencies in that the channel bandwidth is more readily obtainable and the ionospheric delay effects are substantially smaller at L-band frequencies. As noted earlier, all frequencies in both the satellites and user equipment are derived from and synchronized with multiples of the basic 10.23 MHz frequency standard. For example, the carrier frequencies are:

L_1 RF Frequency = 154 x 10.23 MHz = 1575.42 MHz

L_2 RF Frequency = 120 x 10.23 MHz = 1227.6 MHz

2. Multiple Access Properties

Spread spectrum modulation techniques are characterized by good multiple access properties and are obtained in direct sequence spread spectrum by using unique codes. The key multiple access performance parameter of the GPS signals is the generalized cross-correlation performance. All GPS receivers must perform a cross-correlation operation if it is to extract the signal and recover the data. In the GPS signal structure there are two PRN codes used. They are referred to as the C/A and P codes and both exhibit useful properties which will be explained more fully later. The codes serve two major functions. First, they identify each satellite as the code patterns are unique to each satellite and are matched with like codes generated in the user receiver. Secondly, they are used to measure the transit time of the navigation signal by measuring the phase shift required to match like codes. The C/A code is a short relatively easy to acquire code and it provides a gross measurement of time. The P code is a long code which provides a very accurate measurement of time but is difficult to acquire.

3. Form of the Signal Structure

The C/A code which stands for Coarse/Acquisition or Clear/Access is a relatively short code of 1023 bits and has clock rate of 1.023 MBPS. The period is 1 msec. The C/A

codes are formed for various satellites by the modulo-2 sum of two 1023 bit Gold codes designated as G1(t) and G2(t). The C/A codes for the various satellites are selected to provide good multiple access properties for its period. The main advantage for using the Gold codes is not simply a low cross-correlation between all members of the family but that there is a large number of codes all of similar good cross-correlation properties. Because the C/A code repeats itself every millisecond, it is relatively easy for the receiver to match and lock onto the C/A code.

The P or Precision code is also a PRN sequence with a clock rate of 10.23 MBPS and a period of exactly one week. It is formed by the product of two PRN codes, designated X1(t) and X2(t + n T) where $0 \leq n < 36$ and T is the period. Notice that code X2 has a period 37 bits longer than X1. The formulation of the P code which is actually used is then $XP_i(t) = X1(t)x2(t+n_iT)$ where $0 \leq n_i \leq 36$ and T is the period. The period of a product of P codes of relatively prime period is the product of the periods [Ref. 28]. Thus if the P codes were allowed to continue without being reset, it would continue without repeating for slightly more than 38 weeks. The overall period has been effectively subdivided so that each satellite gets one period which is non-overlapping with every other satellite.

The two product codes which make up the P code are initialized at midnight each Saturday. GPS system time is

counted from this initialization of the P code each week. Counting is accomplished by counting the epochs (recurrences of the initial state) of the X1 code generator that occur every 1.5 seconds. The count of the X1 epochs, called the z count, rises to 403,199 at the end of each week when it is re-initialized to zero. If the receiver knows the z-count, it knows where to start searching to match and lock onto the P code.

4. Signal Characteristics

Fig. 31 illustrates how the signals are generated from the navigation subsystem aboard a GPS satellite. L_1 and L_2 are modulated by either/both a 10.23 MHz PRN P code or by 1.023 MHz PRN C/A code. Each of these two binary signals has been formed by a P code or a C/A code which is modulo-2 summed with a 50 BPS data stream to form $P \oplus D$ and $C/A \oplus D$, respectively.

The L_1 carrier is quadriphase modulated where the in phase component of the carrier is modulated by the P signal ($P \oplus D$) and the quadrature carrier component is modulated by the C/A signal ($C/A \oplus D$). The L_2 carrier is normally biphased modulated by the P signals ($P \oplus D$) but can be commanded to switch to the C/A signal ($C/A \oplus D$). The 50 BPS data which is modulo-2 summed with the P or C/A codes contains telemetry, satellite clock corrections, satellite ephemeris, ionospheric model parameters, the P code acquisition word and an almanac. It is the subject of the next section.

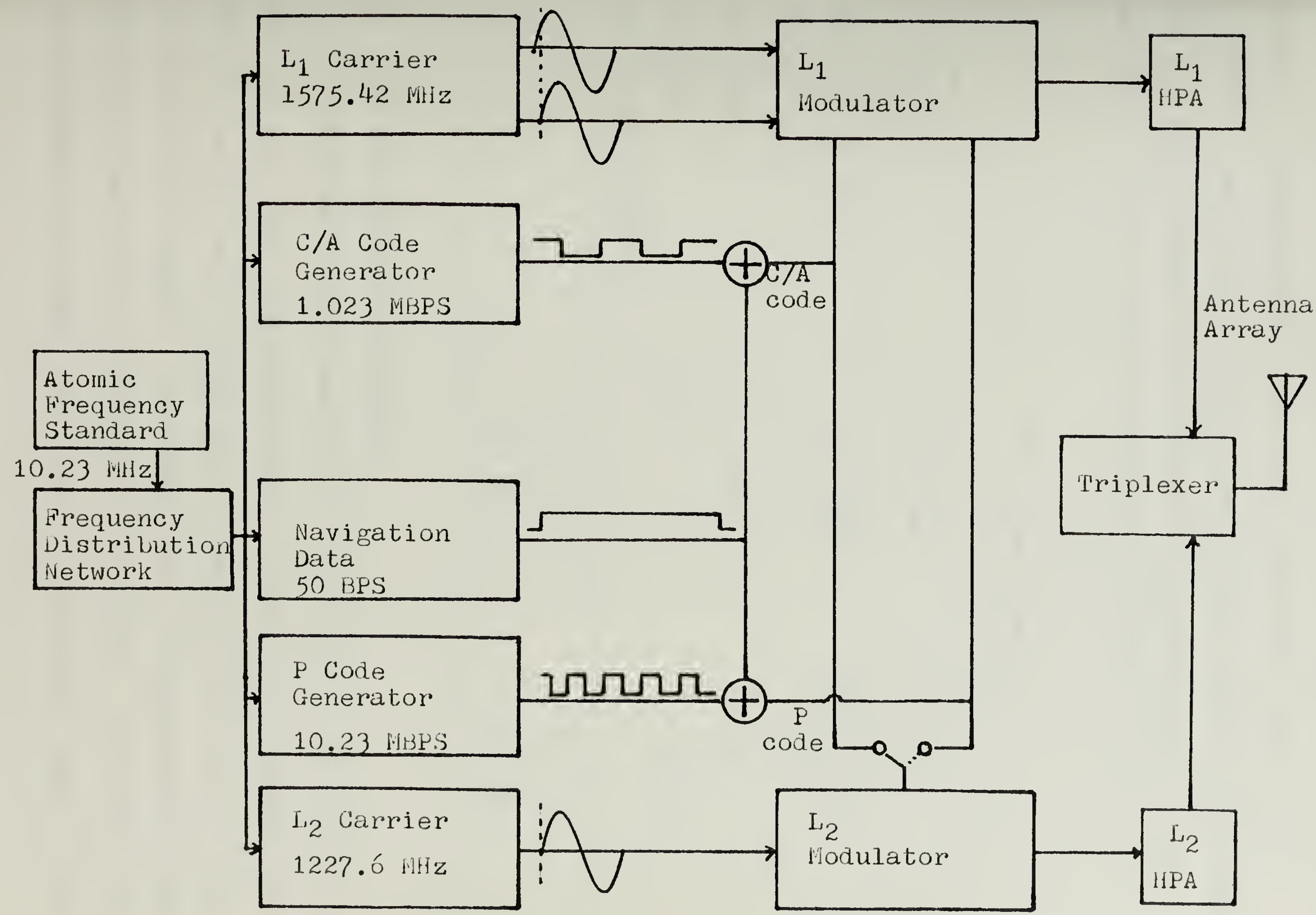

Fig. 31 Navigation Signal Generation

Table 18 is a summary of characteristics of the GPS signal. Included are the typical received signal power levels. The received signal power levels are at the output of a 0 dBIC antenna with RH circular polarization. The satellite is at an elevation angle greater than 5°.

Table 18 GPS Signal Summary

Parameter	C/H Signal	P Signal
Code Clock Rate	1.023 MBPS	10.23 MBPS
Code length	1023 bits	6×10^{12} bits
Data Rate	50 BPS	50 BPS
Carrier	L_1	L_1 and L_2
Rcv'd Sig Strength		
L_1	-160 dBw	-163 dBw
L_2	-166 dBw	-163 dBw

F. THE GPS NAVIGATION MESSAGE

The GPS navigation message is the information supplied to the GPS user from the satellite. It is in the form of a 50 bit per second data stream that is modulated on both L_1 and L_2 navigation signals. The data clock is synchronized with C/A epochs and the X1 code generator epochs. The data message is contained in a data frame that is 1500 bits long. It has

five subframes each of which contains system time and the C/A to P handover information. The first subframe contains the satellite's clock correction parameters and ionospheric propagation delay model parameters. The second and third subframes contain the satellite's ephemeris. The fourth subframe contains provision for a message of alphanumeric characters. The final subframe is a cycling of the almanacs of all the satellites (one per frame) containing their ephermerides, clock correction parameters and health. The almanac information is for user acquisition on yet to be acquired satellites. A more detailed description of the subframes is contained in the following paragraphs.

Fig. 32 illustrates the data format of the navigation message. Each subframe contains 300 bits, is six seconds long and begins with a TLM and HOW word. The TLM or telemetry word contains, at the appropriate time, primary upload status messages and diagnostic information used by the control segment. The HOW or handover word contains the z-count which facilitates the receiver's transition from the C/A code to the P code. The z-count is defined as the number of 1.5 sec and epochs of the X1 code generator since the beginning of the week. In order to acquire the P code, the 50 BPS data stream contains a new handover word (HOW) each six second subframe. The HOW word, when multiplied by four gives the z-count at the beginning of the next six second subframe. Thus, if the receiver knows the subframe epoch times and the HOW word, it

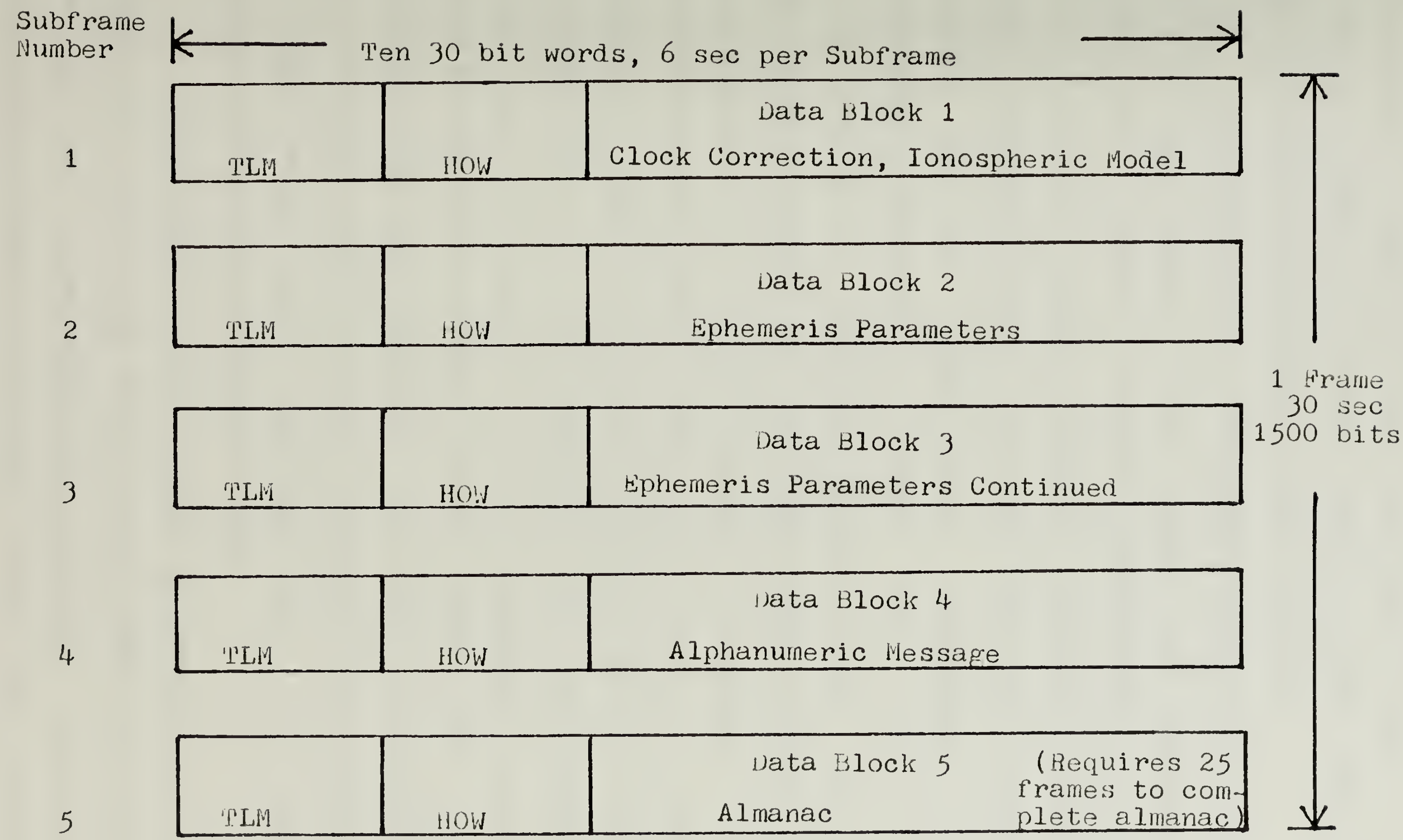

Fig. 32 Navigation Data Format

can properly align the locally generated P code with the received P signal at the next subframe epoch. Both the TLM and HOW words are generated by the satellite.

The remainder of the navigation message is generated by the control segment which includes three blocks of data plus a block reserved for special alphanumeric messages. The first data block contains satellite frequency standard corrections, associated age of data word (AODC) and ionospheric propagation delay model coefficients. The purpose of the clock correction parameters is to provide the user with a description of the satellite's time offset from GPS time. The offset is not constant because the satellites atomic frequency standard has definite drift characteristics. In addition to the clock correction coefficients, data block 1 contains ionospheric propagation model coefficients which are used by the single frequency user, i.e. the Magnavox Z set. The propagation model is not as accurate as the two frequency correction provided by most GPS receivers but was adequate for the less accurate, low cost Z receiver. The AODC word describes the last time the satellite clock corrections were updated and provides the user with a confidence level in his ability to predict the satellite's clock offset.

Data blocks 2 and 3 contain the satellite's ephemeris predictions and the age of data word (AODE) which indicate the last time the parameters were uploaded. The ephemeris prediction parameters only apply for the time period that they

appear. This is approximately one hour but if an upload does not occur or is delayed the parameters reasonably describe the satellite's orbit for one to five hours. After this time, refreshed ephemeris parameters are required for nominal navigation accuracy.

Data block 4 is reserved for special messages. Although not used during Phase I testing, future plans indicate that the special alphanumeric message block will be used by the control segment to pass on any important information to all would be users. An example might be the recommended non-use of a particular satellite.

The final subframe, subframe 5, contains the almanac data. It includes ephemeris, clock correction parameters, and atmospheric delay parameters for all the satellites. This data is an abbreviated version of the original clock and ephemeris correction parameters and is only used in acquiring new satellites. The total almanac exceeds the total capacity of a single subframe (5th) so it is transmitted on a rotating basis. Therefore, it requires 25 frames or 750 seconds for a receiver to obtain an entire almanac.

The data frame repeats itself every 30 seconds except the almanac data which rotates through 25 subframes. Periodically (nominally every hour) the data in data blocks 1, 2, and 3 are refreshed by the satellite's navigation subsystem and apply to the new period. The navigation subsystem has stored 26 one hour periods of ephemeris and clock correction parameters

which are uploaded to the satellite daily by the control segment. Almanac data is only refreshed by the daily satellite upload. To minimize the effects of errors a Hamming (32,36) error correcting code is employed on the 50 BPS data stream.

G. ACQUISITION AND TRACKING

Once the best four satellites are selected from all that are visible, the receiver must first acquire the C/A signal from a particular satellite. A sampling process of the required signal is used to detect and lock onto the C/A signal and decode satellite data. To acquire the signal, the receiver must undertake a sequential detection operation to find whether or not the received signals are approximately matched in code, code phase and Doppler frequency shift. When no match is detected, these parameters must be changed repeatedly until a match is detected. Once an approximate match is found it is necessary to lock onto code phase and carrier frequency and phase. When this is accomplished, the receiver can demodulate the signal and recover the data. All GPS receivers utilize a microprocessor to predict pseudo-range and delta-pseudo-range from the code and carrier phase shifts. Thus, the microprocessor is available to accomplish many of the functions required in acquiring and tracking of the navigation signals. For example, the receiver navigation processor selects the best satellites but it also estimates the expected Doppler shift on the signal which may be as great as $\pm$ 2kHz.

Therefore, the use of the microprocessor achieves accurate tracking performance while retaining design flexibility for application to a wide variety of GPS users.

The acquisition process in all GPS receiver requires a cross-correlation operation if the receiver is to lock on and track the signal as well as recover the data. The actual received signal arrives at the receiver at the RF frequency and must undergo a down conversion operation to recover a coherent carrier. Fig. 33 illustrates how a coherent carrier may be generated. Once a coherent carrier is recovered the remainder of the receiver can be implemented with either a delay lock or tau-dither coherent tracking loop. A non-coherent tracking loop scheme is also possible. The function of the tracking loop is that it maintains the locally generated C/A code replica in synchronization with the received C/A signal. This permits the C/A code shift to be measured and a pseudo-range computed. In the tau-dither implementation the code replica phase is dithered between early and late samples separated by one code chip interval and the difference in the cross correlation is computed. The delay lock loop (DLL) on the other hand develops its error signal by simultaneously correlating advanced and retarded replica codes with the received code signal. Generally, the DLL has slightly better performance. Fig. 34 illustrates the basic components of a coherent delay lock loop. Also shown in Fig. 30 are the

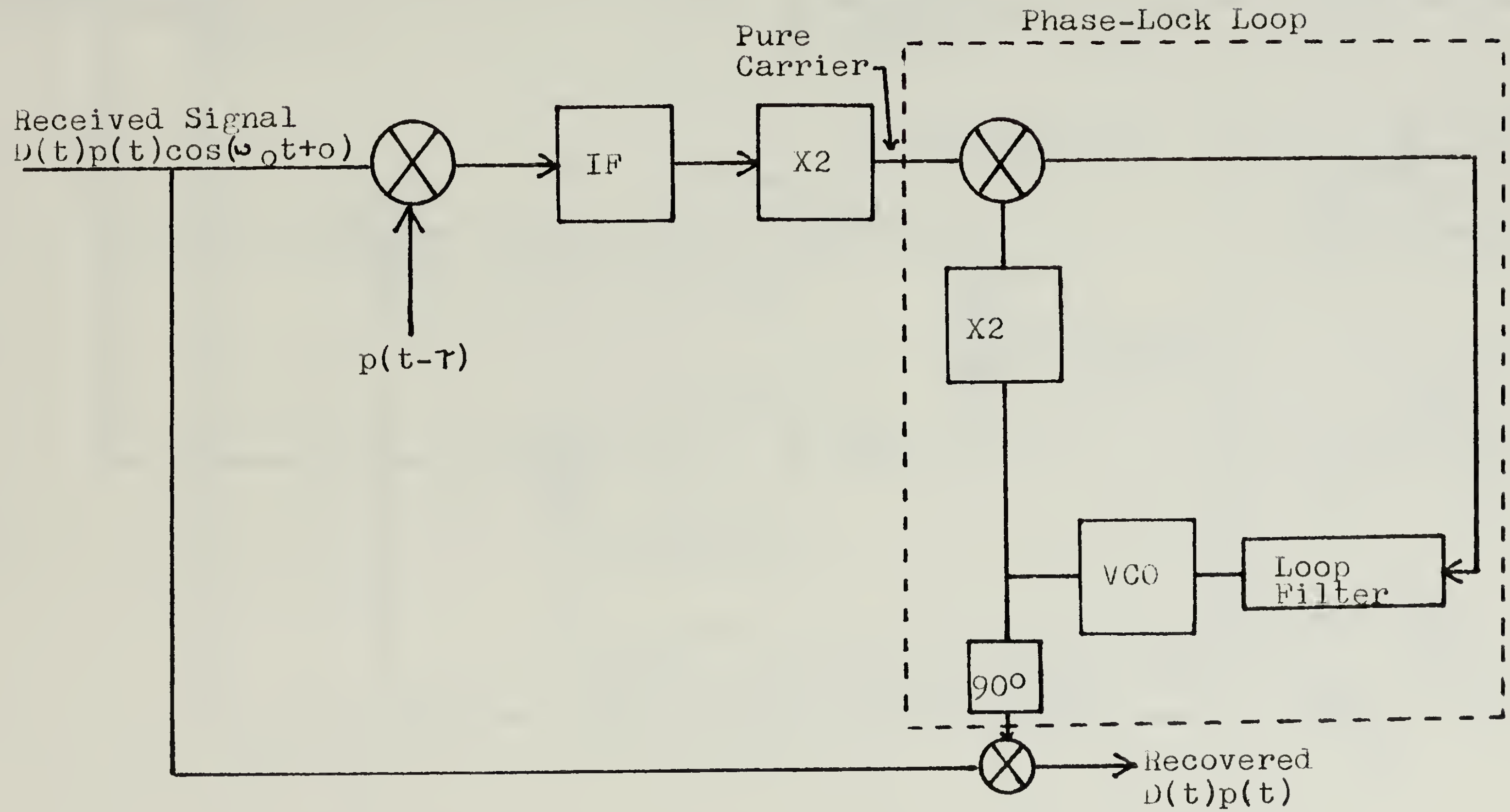

Fig. 33 Carrier Recovery Using the Received Signal [Ref. 29]

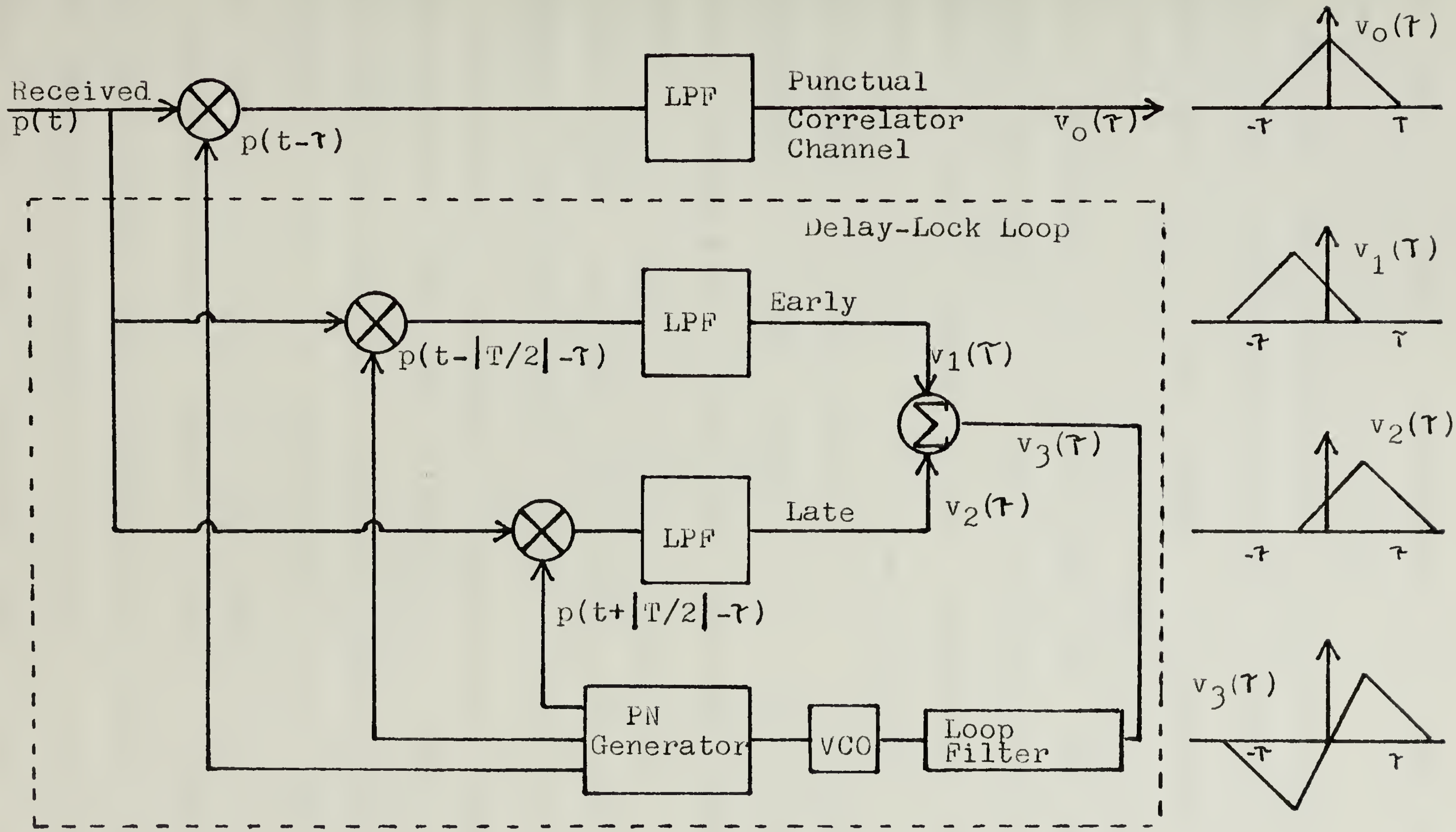

Fig. 34 Coherent Delay Lock Loop [Ref. 30]

various outputs voltages of the punctual, early and late correlators as well as the error voltage.

Once the code tracking process has been accomplished by either of the two mentioned processes, the BPSK data can be recovered from the punctual channel. The received signal, either the P or the C/A code signal is applied to a mixer where it is correlated with the punctual code. The output of the mixer and bandpass correlator is then the BPSK signal. The signal can then be demodulated by a conventional BPSK demodulator, e.g. a Costas loop. A simplified block diagram of a GPS receiver is illustrated in Fig. 35. It illustrates one implementation of a GPS receiver using a non-coherent DLL for code tracking and a Costas Loop for data demodulation. The majority of the Magnavox receiver designs employ a composite non-coherent tau-dither code tracking loop and a Costas/AFC (Automatic Frequency Control) circuit for data demodulation.

The discussion of signal acquisition and tracking so far has assumed that the locally generated code replica and the received signal code were very close to synchronization (approximately 1 chip). At the beginning of the signal detection and acquisition process this will probably not be the case. The receiver will be required to search through a time/frequency domain where the time uncertainty will be caused by range dispersion and unknown clock biases. The frequency uncertainty will be caused by user and satellite motion (Doppler shift). Because there are only 1023 chips in the C/A

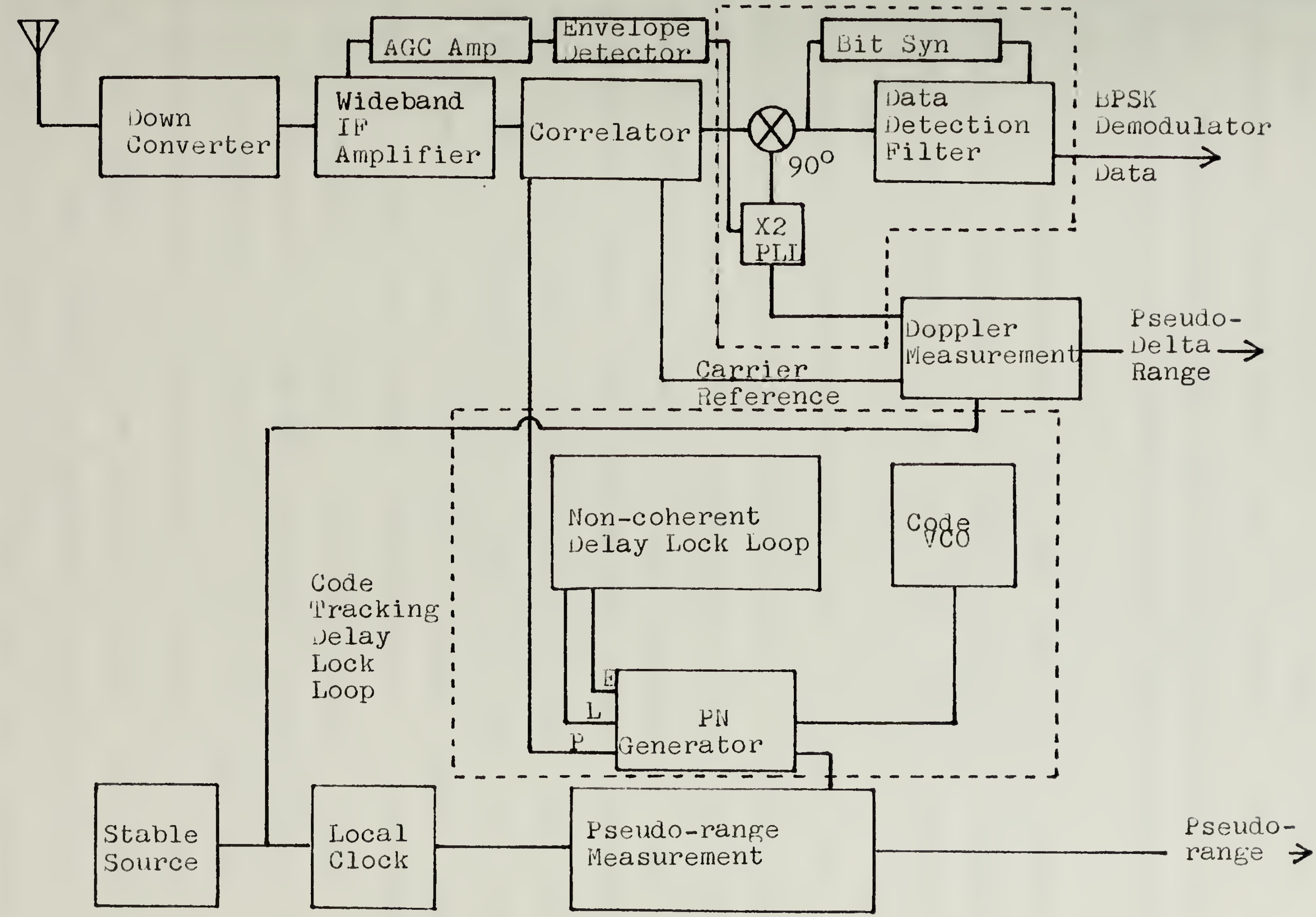

Fig. 35 Simplified Block Diagram of a GPS Receiver [Ref. 31]

code and the navigation processor can estimate doppler shift, the receiver's search process can be limited to a short time (less than a minute). The total acquisition time for four satellites using a four channel receiver would be this value for a single channel receiver.

The normal sequence of events once the receiver has acquired and is tracking the satellite signals is to demodulate the data stream using the C/A code. This is because of the relative ease of acquiring the C/A code. The C/A code can be used for navigation purposes but it only provides limited accuracy (approximately 100 meters). The code chip width for the P code is 97.75 nsec while the C/A code chip width is 977.5 nsec. Receivers can be designed so that they can track the incoming code with an RMS error on the order of .01 of the chip width at a signal to noise ratio (SNR) of 30 dB. This translates to a .3 m rms error using the P code or 3 m rms error using the C/A code to measure pseudo-range [Ref. 32]. Once data has been demodulated by the C/A code there is normally a transfer to the more precise P code. This is facilitated by the HOW word which is contained in the data. The HOW word is synchronized with the P code and indicates the point in the incoming P code that will occur at the next change, i.e. in the next six seconds. The receiver generated P code can then be shifted to be synchronized with the designated point in the incoming P code when triggered by the change in the HOW word. This completes the C/A to P code

transfer and now data demodulation and navigation solutions can be accomplished with the accurate P code.

Due to the limited transmitting power of the satellites and the nature of the modulation technique (spread spectrum) the GPS receiver must accurately track a navigation signal at very low signal levels, usually well below the thermal noise level of the receiver. (See Table #7, GPS Signal Summary.) In normal operation, i.e. non-interfering environment and satellites above 5° elevation angle, the receiver is designed to operate at a carrier to noise power ratio (C/N_o) of 30 dB-Hz. The typical receiver suspends P codes tracking and tracks on the less accurate C/A code when the C/N_o becomes less than 26 dB-Hz. When the C/N_o drops below 20 dB-Hz, the signal is lost and the receiver must attempt to acquire the satellite from its stored almanac data. Data from Phase I testing indicates that in a benign environment receivers experience a typical C/N_o of 38 dB-Hz.

H. ERROR SOURCES

The ability of a GPS user to accurately determine his position depends on two factors. The first is the accuracy with which the user can determine the true slant range between himself and the satellites. The user's ability to determine the true slant range is affected by the environment and the equipment he is using to calculate the slant range. The second factor influencing the user's accuracy is the geometry of the

satellites the user is using. The proper choice of the "best" four satellites can greatly affect the accuracy of the navigation solution. All error sources in the GPS system can be associated with one of these two factors.

1. <u>Factors Which Affect Slant Range</u>

In determining the true slant range, the user's environment plays a significant role. The effects of relatively and its effects on frequency must be accounted for. The relativistic frequency shifts are caused by two effects. Both depend on the user's location. They are the difference in gravitational potential between satellite and user and their velocity differences. Much of this relativistic effect, as indicated earlier, can be corrected by adjusting the satellite's frequency standard slightly below the desired frequency. The user's dynamics can also be considered as part of the user's environment and it contributes to errors in the determination of slant range. The actual effect will depend upon the receiver's static accuracy capability, navigation measurement update and external aiding. Dynamic effects can partially be compensated for by special receiver design (for example clock stability), external aiding with an inertial measuring unit (IMU) and by Kalman filtering.

Multipath is another phenomena which is characteristic of the user's environment. It exists because direct path signals and signals reflected from some surfaces (e.g. sea water, metallic surfaces, buildings, etc.) combine at the

receiver's antenna. Due to differing path lengths between the direct and reflected path, the phases of the signal are such that they add or subtract causing constructive or destructive interference. This causes errors in the determination of slant range. The PRN code modulation of the GPS signal provides an inherent rejection of multipath interference signals which do not occur within one code width of the direct signal time delay. In those cases when the multipath signal is within 1 or 1 1/2 PRN chips of the direct signal there is no practical way to correct the resulting erroneous measurement. Proper antenna design has been found to greatly reduce the problem of multipath.

Another environmental problem which causes errors in the computation of slant range is low signal strength. The low signal strength may be caused by interference (jamming, multipath, etc.). The signal strength depends on the satellite's effective isotropic radiated power (EIRP) and is affected by space losses, antenna pointing, polarization losses, antenna gains and the receiver's system losses. The noise contribution is primarily determined by the user's pre-amp design. As indicated earlier, the satellite's EIRP and reciever's design have permitted enough margin in signal strength that in a benign environment (tracking above 5°) 6 dB peak fades will not cause the receiver to lose lock or inhibit signal acquisition. The Phase I signal provides a margin of 8 to 10 dB above threshold even at low elevation angles. At higher elevation angles,

the signal strength (C/N_o) is in excess of 40 dB-Hz and fading becomes even less of a problem.

Data generated by the early Navy's navigation satellite series, TIMATION, indicated that irregularities in the atmosphere could have appreciable effects on navigation accuracy. The two layers which were identified as contributing the most errors were the tropospheric and the ionosphere. It was determined that the tropospheric induced delay error was the result of ray (signal) bending effects that was caused by water vapor and other tropospheric constituents. The tropospheric effect was found to be frequency independent and primarily sensitive to receiver altitude and line-of-sight elevation angle. The range measurement will exhibit an increase from above 2 meters at zenith to approximately 100 meters on the horizon due to tropospheric effects [Ref. 33]. The models used by the receiver to account for tropospheric delays do not involve meteorological parameters, are fairly simple and use only the elevation angle to the satellite.

The ionospheric delay was found to be caused by the integrated electron count over the signal path and the refraction effect of the layer. Thus, the effect is dependent on both the character of the ionosphere and the elevation angle to the satellite. Unlike the troposphere, the propagation delay caused by the ionosphere is frequency dependent. The magnitude of the delay is also affected by the time of day, solar activity, geomagnetic latitude and the condition of the

ionosphere. Two methods are employed in GPS to compensate for ionospheric delay errors. The first is an a priori modeling estimation of the delay which requires reception of only a single frequency. It provides reduced accuracy and is only used in the low cost GPS receivers. The second method is a real-time dual frequency solution of the ionospheric delay. A precise correction can be made by making use of measurements at the two L band frequencies and making use of the approximate inverse square law behavior of the ionospheric delay. The magnitude of the delay can be calculated by a comparison of the two frequencies and removed with a high degree of accuracy.

The other major contributor to errors in the calculation of slant range are errors caused by the equipment. In any RF ranging system, there will be errors caused by the processing of signals by the transmitter and receiver hardware. One cause of errors in the equipment hardware is referred to as group delay. It is the delay from uncertainties caused by the processing and passage of signals through the satellite and receiver equipment. This is the same group delay described earlier which was associated with RMS equipment. The magnitude of these delays are calibrated during tests of the equipment and accounted for during normal operation. Another source of errors in the system's equipment is mechanization errors. They originate in the navigation processor aboard the satellites and in the

receiver and are caused by finite computer bit resolution, mathematical approximations, algorithm uncertainities and timing delays inherent in the required computations. Theoretical formulation of the impact of these errors is in close agreement with Phase I findings.

Another major contributor to equipment induced errors comes from the control segment. They provide information through the satellites to the user on the satellites predicted ephemeris and clock drift characteristics. Differences in the satellite's actual versus predicted position in its orbit can greatly influence the accuracy of the user's navigation solution. Although the satellite clocks use high stable atomic frequency standards, they may deviate significantly from GPS time. The offset is corrected by the model used by the receiver. It employs correction coefficients which are calculated by the control segment. Errors caused by the model can also greatly influence the accuracy of the user's navigation solution. Through the use of better monitoring and tracking by the control segment and frequent uploads to the satellite, these errors can be minimized.

Table 10 is a summary of those uncorrected error sources which impact upon the accuracy of the user's navigation solution by affecting the determination of slant range. It reflects the uncorrected error source, the magnitude (one sigma) of the user equipment range error (UERE) and the segment responsible for that error.

Table 19 Range Error Budget for P-Code Navigation [Ref. 34]

Uncorrected Error Source	User Equipment Range Error(1σ)	Category
Satellite Clock Errors Ephemeris Errors	4.6	Control Segment
Atmospheric delays	2.4-5.2	User-environment
Multipath	1.2-2.7	User's environment
Receiver Noise and Vehicle Dynamics	1.5	User Segment
Root Sum Square(RSS)	5.5-7.6	

2. Geometry of Satellite Configuration

The second factor which influences the user's accuracy is the geometry of the configuration of four satellites and the receiver. It is this geometry which transforms slant range errors into position navigation errors. A figure of merit which describes how good this geometry is between the satellites and user is referred to as Geometric Dilution of Precision (GDOP). It is independent of the coordinate system used. The value of GDOP is a composite measure that reflects the influence of satellite geometry on the combined accuracy of the user time (user clock offset) and the user's position. It is expressed as $GDOP = \sqrt{(PDOP)^2 + (TDOP)^2}$ where PDOP is an estimate of the range equivalent of the user's position uncertainity and TDOP is an estimate of the range equivalent

user's clock bias. Small values of the GDOP parameters indicate a good arrangement in the geometry of the satellites and correspondingly small error in the position and time fixes. It can be shown that PDOP can be determined geometrically by relating it to the volume of a special tetrahedron where the four satellites and the position of the user define the vertices. If PDOP is proportional to 1/V, or PDOP becomes smaller as the volume of the tetrahedron increases, then GDOP decreases and position accuracy improves. The volume of the special tetrahedron is maximum when one satellite is at the user's zenith and the other three are separated by 120° and are as low on the horizon as permitted by the user's antenna pattern. Fig. 36 illustrates good and bad PDOP. Note that these characteristics of geometric additions of error are not only applicable to GPS but rather are to all position determination operations using range measurements for trilateration which includes RMS.

The specification for user accuracy in the GPS is expressed in terms of User Equivalent Range Error (UERE). See Table 19. The navigation accuracy (one sigma) can be estimated as the UERE times GDOP. For example if the UERE were within the Phase I budget error of 6 meters and GDOP was 3, then the navigation accuracy (one sigma) estimate would be 18 meters.

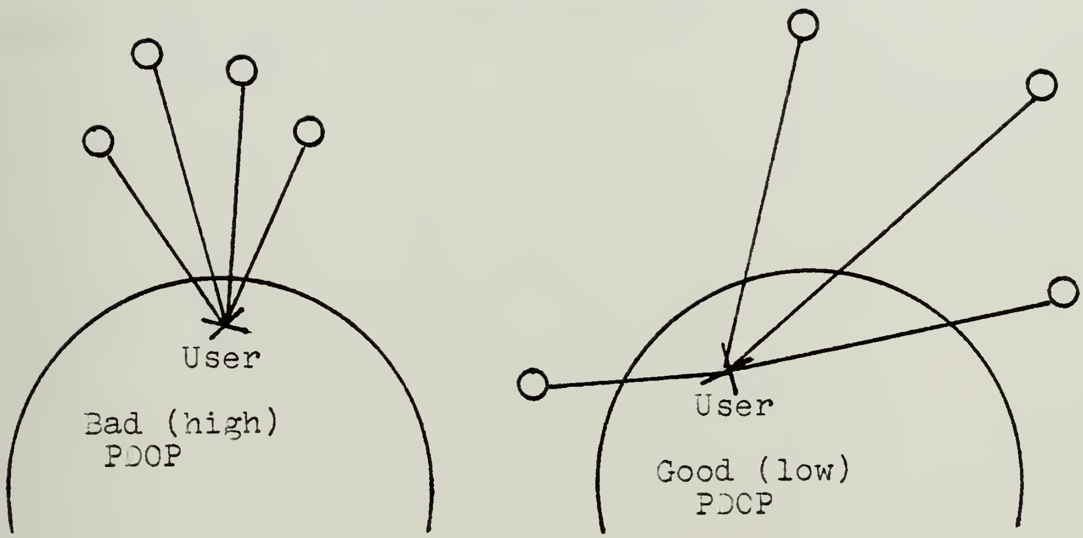

Fig. 36 Geometry of PDOP

APPENDIX C

MAP OF DEMONSTRATION AREA

This appendix contains the maps of the two major areas, Nacimiento Valley and Upper Milpitas Valley, where the demonstration was conducted. Indicated on each map are the reference points used. Survey data for the reference points may be found in Appendix E. The original map sheet from which these maps came is entitled, Hunter-Liggett Special, Series V7955, Edition 1-DMATC dtd 1973.

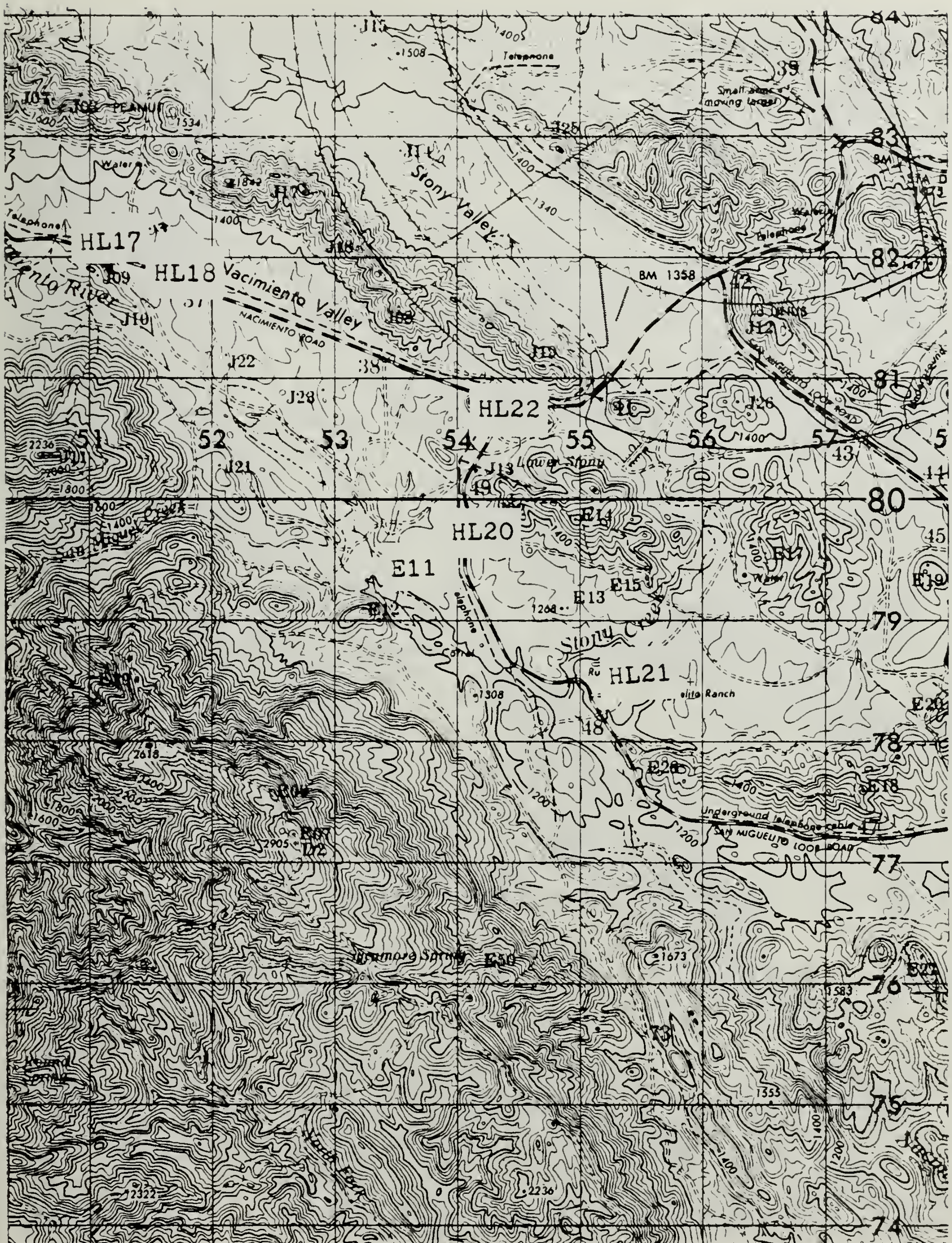

Fig. 37 Nacimiento Valley Map Including Reference Points

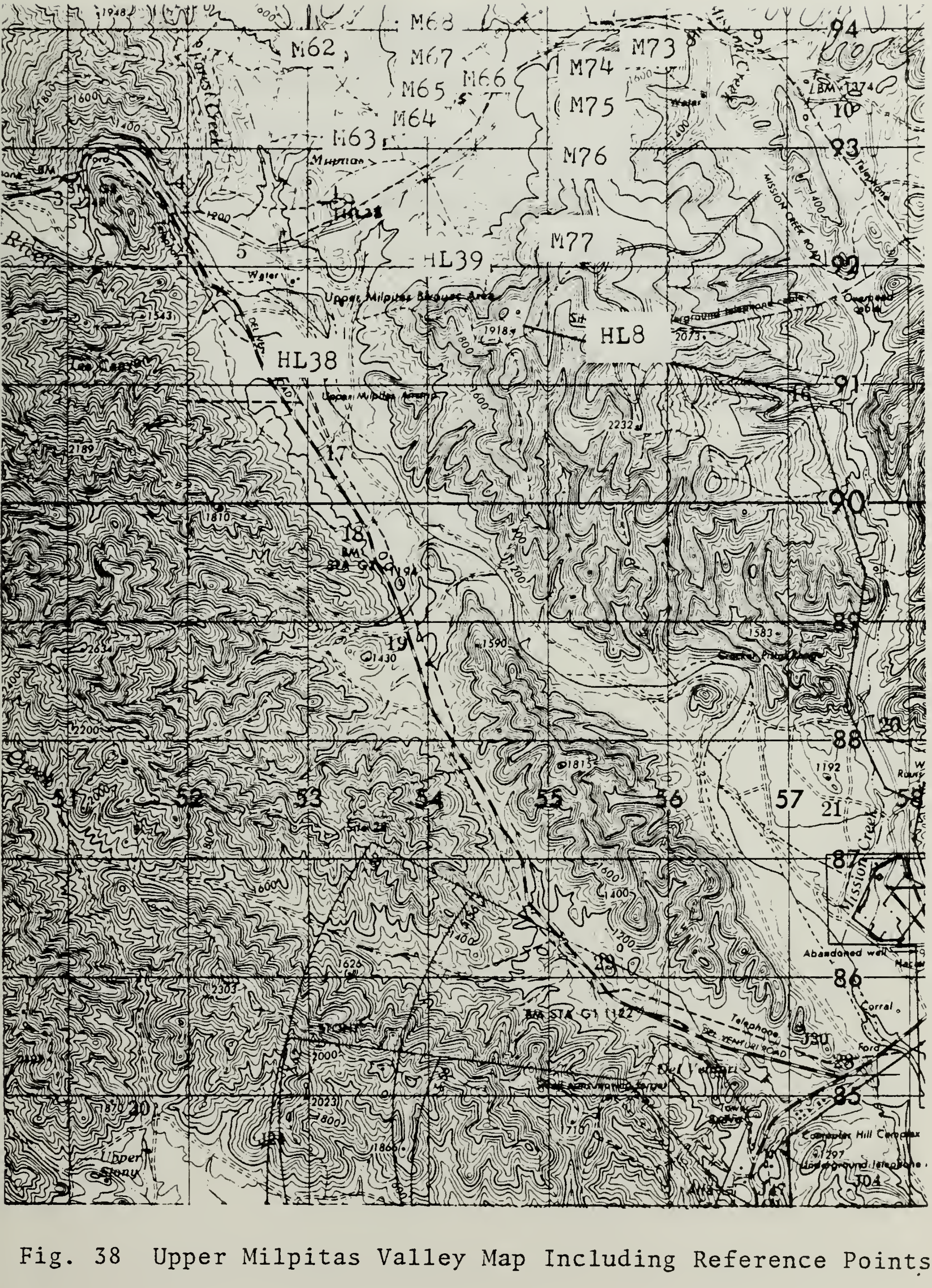

Fig. 38 Upper Milpitas Valley Map Including Reference Points

APPENDIX D

SATELLITE VISIBILITY GRAPHS

This appendix contains computer predictions of satellite elevation angles, azimuth angles and azimuth and elevation angles for four satellite visibility. These predictions were used to determine satellite visibility for the demonstration period, 13-17 October 1980. Although the predictions were done for 1 October 1980, satellite visibility can be determined using these graphs for any particular day by knowing that the satellites become visible 4 minutes and 3 seconds earlier each day. These predictions are specific to Fort Hunter Liggett.

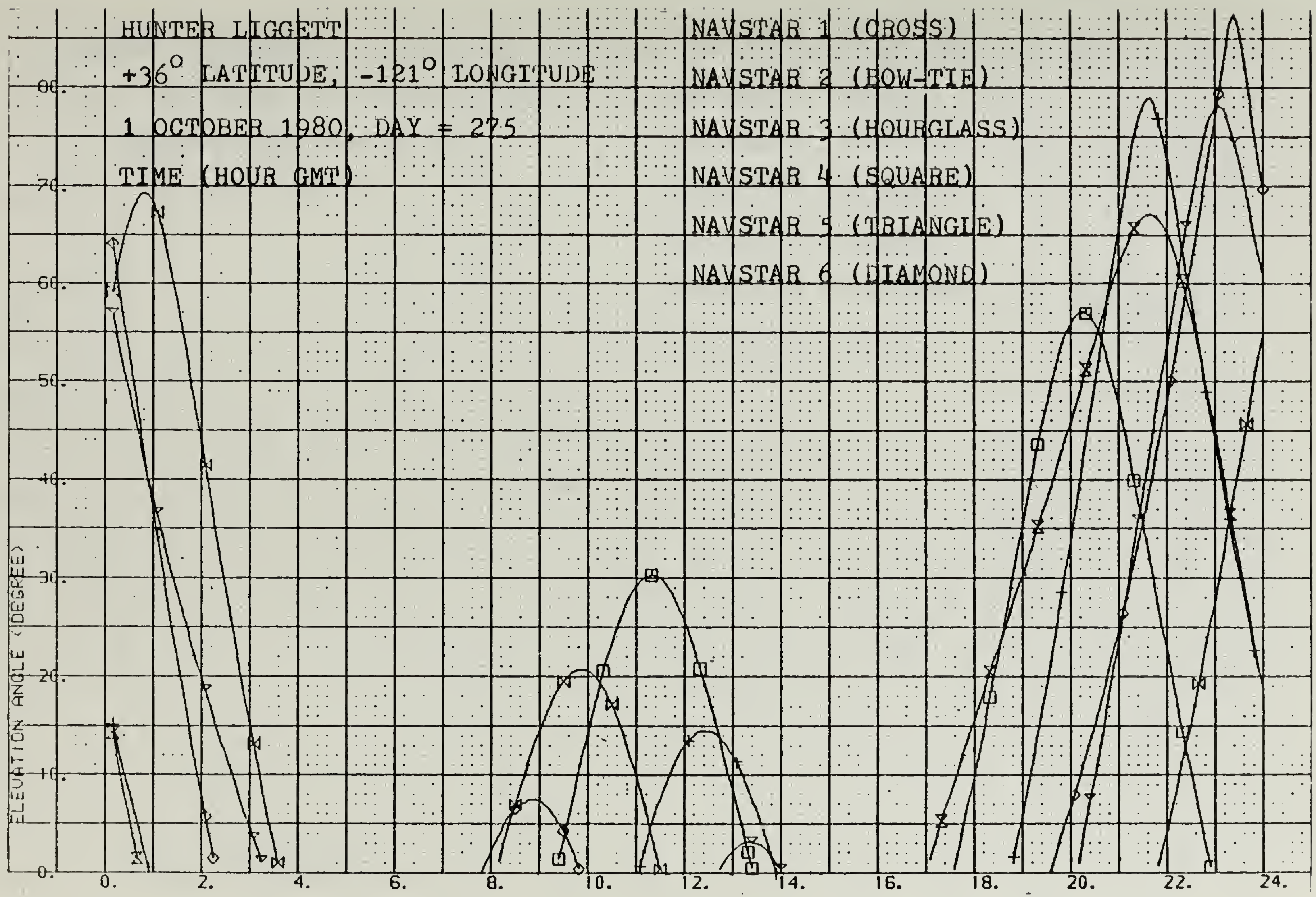

Fig. 39 Elevation Angles To Visible GPS Satellites

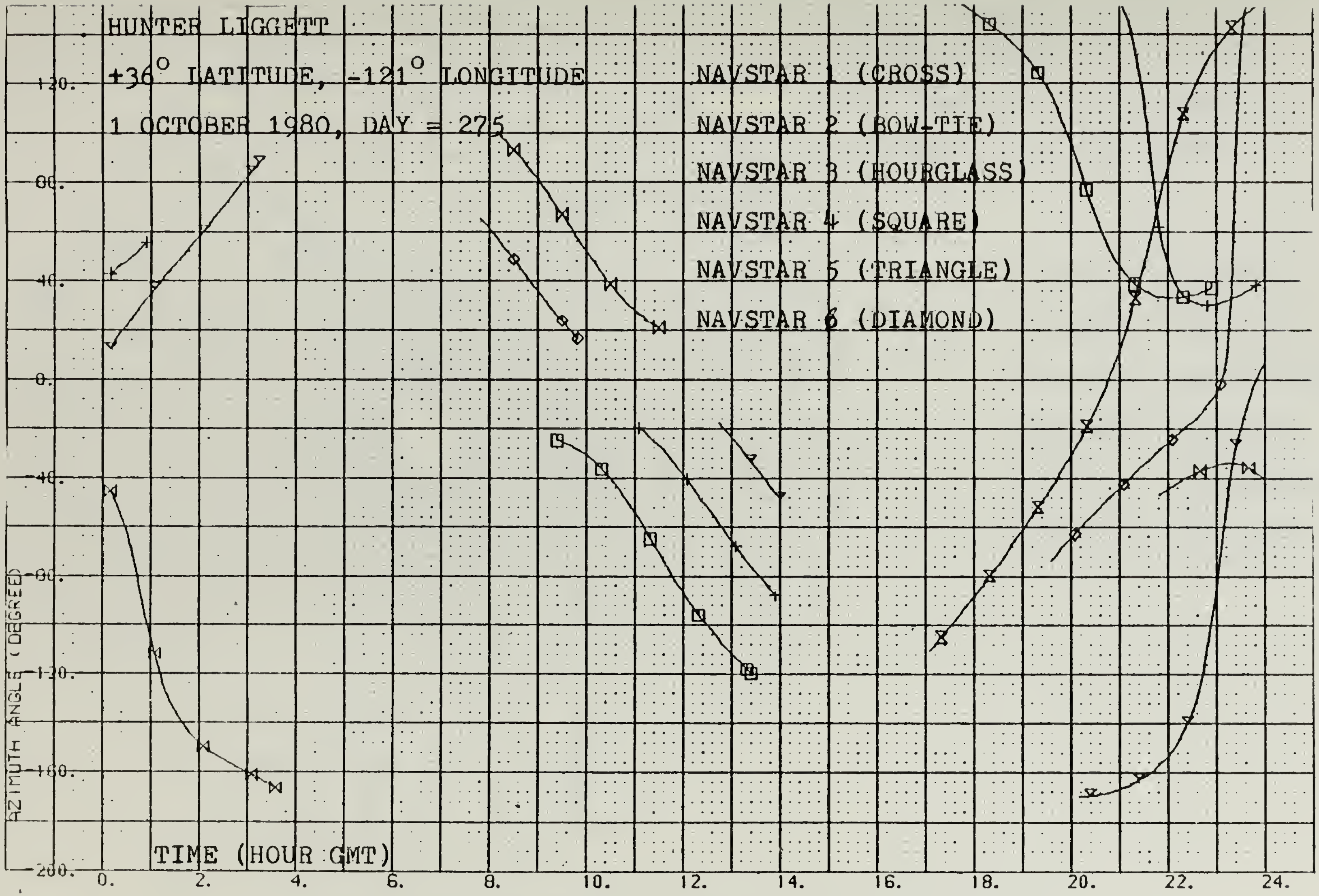

Fig. 40 Azimuth Angles To Visible GPS Satellites

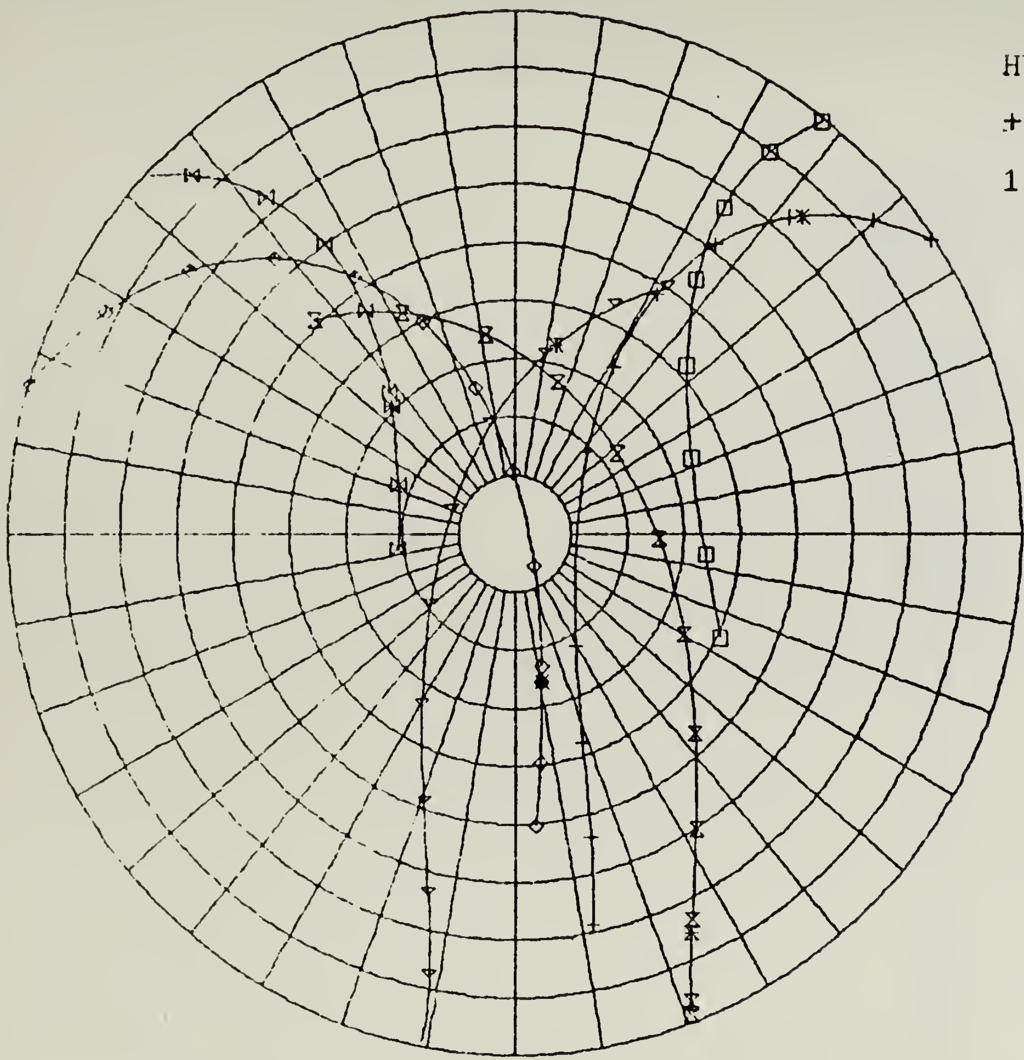

Fig. 41 Azimuth And Elevation For Four Satellite Visibility

APPENDIX E

DEMONSTRATION SURVEY POINTS AND DATA

Contained in this appendix is the survey data for the reference points used throughout the demonstration. The survey information was obtained from two sources which are listed below. These reference points are plotted in Appendix C.

1) Precise Geodetic Survey
Fort Hunter Liggett and Camp Roberts, California
30th Engineer Battalion (T.) (A.)
Conducted 1978

2) Precise Geodetic Survey
Hunter Liggett Military Reservation, California
Defense Mapping Agency
Topographic Center
Conducted 1975

TABLE 20

DEMONSTRATION SURVEY POINTS AND SURVEY DATA

Reference	Northing	Easting	Altitude
BM 198-14	3 991 409.7	655 604.8	752.6
M77	3 992 164.2	655 314.5	729.2
M77 RM1	3 992 156.9	655 300.3	729.2
M77 RM2	3 992 176.0	655 325.9	729.2
M76	3 993 004.4	655 380.5	616.9
M75	3 993 376.0	655 363.2	609.0
M75 RM1	3 993 379.1	655 352.5	609.0
M76 RM2	3 992 997.1	655 388.3	616.9
M74	3 993 598.5	655 399.6	591.5
M74 RM1	3 993 604.3	655 401.6	591.5
M74 RM2	3 993 590.2	655 402.4	591.5
M73	3 993 860.3	655 765.5	571.3
M73 RM1	3 993 860.8	655 784.8	571.3
M73 RM2	3 993 859.4	655 750.0	571.3
HL-8	3 991 467.3	655 595.3	753.0
M62	3 993 891.7	652 943.4	453.0
HL38	3 992 564.4	653 253.9	438.0
M68	3 994 075.9	653 856.8	505.8
M68 RM1	3 994 085.4	653 854.5	505.8
M68 RM2	3 994 071.1	653 868.0	505.8
HL37	3 991 266.8	652 922.4	355.0
HL36	3 989 566.9	653 625.2	369.3
E-11	3 979 454.5	653 806.3	389.4
HL21	3 978 519.4	655 434.5	386.9
HL18	3 981 910.6	651 572.0	394.7
HL17	3 982 092.2	651 178.8	396.0
HL22	3 980 764.3	654 424.0	398.8
HL22 offset	3 980 753.0	654 375.0	398.8
HL20	3 979 725.3	654 068.6	383.1
HL39	3 992 113.0	654 150.0	422.4

Reference	Northing	Easting	Altitude
M63	3 993 157.2	653 439.8	419.2
M63 RM1	3 993 159.1	653 421.7	419.2
M63 RM2	3 993 159.8	653 449.6	419.2
M64	3 993 312.8	653 805.8	444.6
M64 RM1	3 993 309.9	653 796.8	444.6
M65	3 993 422.3	653 868.5	456.0
M65 RM2	3 993 437.3	653 864.5	456.0
M66	3 993 641.4	653 863.6	477.0
M66 RM2	3 993 636.2	653 879.6	477.0
M67	3 993 982.3	653 910.0	500.4
M67 RM1	3 993 988.4	653 902.5	500.4
M67 RM2	3 993 978.4	653 922.4	500.4

APPENDIX F

HL22 OFFSET, LOCATION AND SURVEY DATA

Diagrammed below is reference point HL 22 Offset which was chosen because of its dense foliage and vegetation. The survey data for this point was obtained using survey data from HL22. The computed data for HL22 Offset is listed below.

Reference	Northing	Easting	Altitude
HL 22 Offset	3 980 753.1	654 375.3	398.8

NOTE: A-1 numbers are in meters.

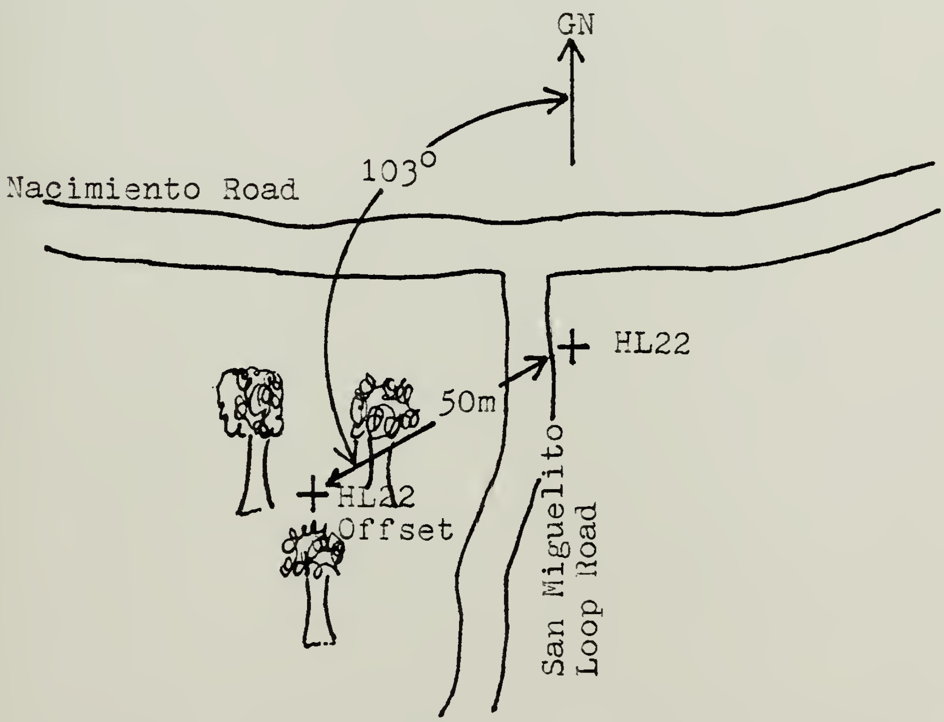

Fig. 42 HL 22 Offset, Location And Survey Data

APPENDIX G

SPOKE TEST DIAGRAM AND SURVEY DATA

This appendix contains the layout and survey data for the Spoke Test which was conducted on the first day of the demonstration. The original reference point which was used to determine the survey location of reference points A - Y was HL 17. The location of the Spoke Test was chosen because the surrounding terrain did not present a masking problem, and there was a variety of vegetation.

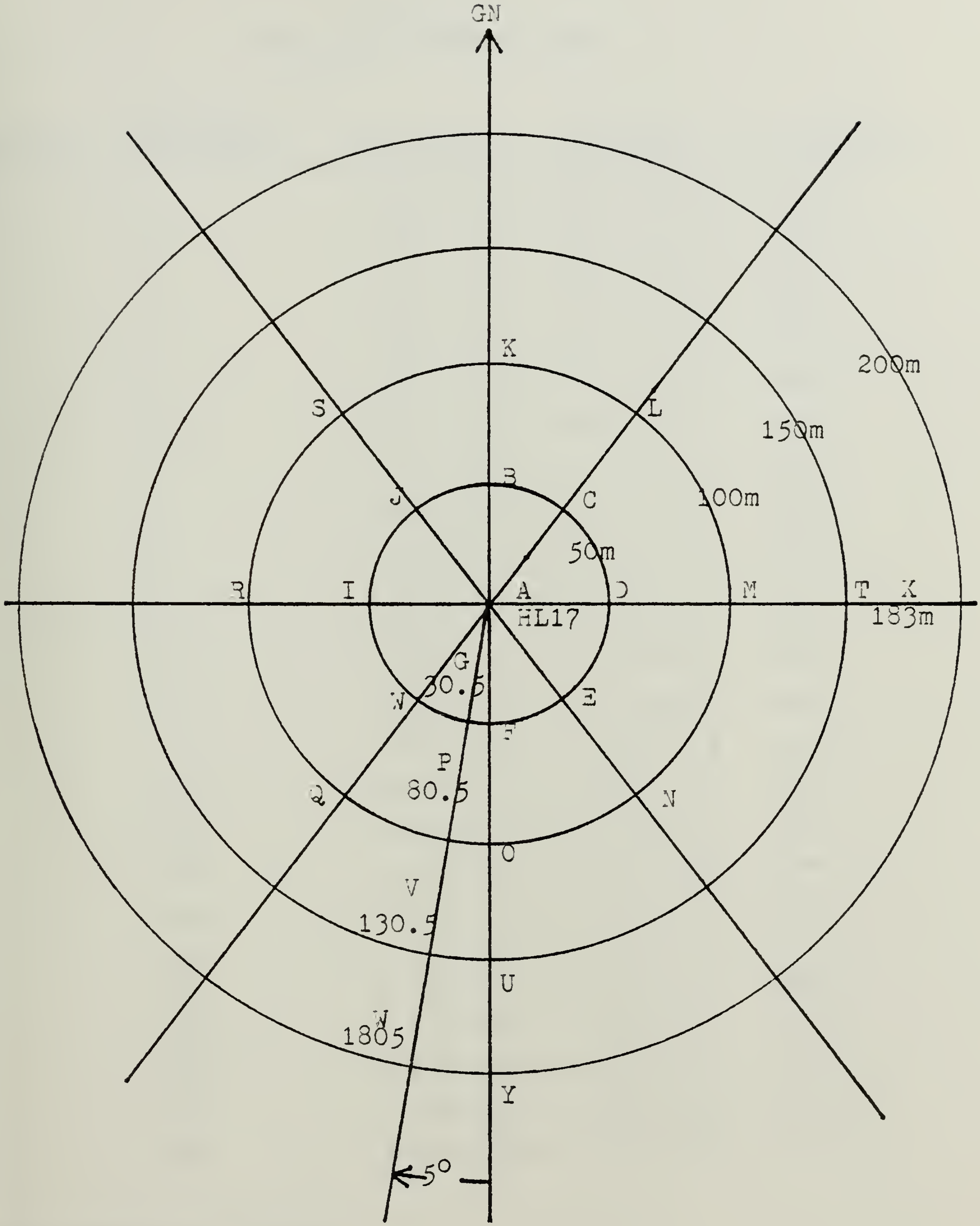

Fig. 43 Spoke Test Diagram

TABLE 21

SPOKE TEST SURVEY DATA

Reference	Distance to Reference	Northing	Easting	Altitude
A	--	3 982 092.2	651 178.8	396.0
B	50	3 982 142.2	651 178.8	396.0
C	50	3 982 127.5	651 214.2	396.0
D	50	3 982 092.2	651 228.8	396.0
E	50	3 982 056.9	651 214.2	396.0
F	50	3 982 042.2	651 178.8	396.0
G	30.5	3 982 061.9	651 176.2	396.0
H	50	3 982 056.9	651 143.5	396.0
I	50	3 982 092.2	651 128.8	396.0
J	50	3 982 056.9	651 143.5	396.0
K	100	3 982 192.2	651 178.8	396.0
L	100	3 982 162.9	651 249.5	396.0
M	100	3 982 092.2	651 278.8	396.0
N	100	3 982 021.3	651 249.5	396.0
O	100	3 981 992.2	651 178.8	396.0
P	80.5	3 982 012.2	651 171.8	396.0
Q	100	3 982 021.3	651 249.5	396.0
R	100	3 982 092.2	651 078.8	396.0
S	100	3 982 162.9	651 249.5	396.0
T	150	3 982 092.2	651 328.8	396.0
U	150	3 981 942.2	651 178.8	396.0
V	130.5	3 981 962.2	651 167.4	396.0
W	180.5	3 981 912.4	651 163.1	396.0
X	183	3 982 092.2	651 361.8	396.0
Y	200	3 981 892.2	651 178.8	396.0

* All numbers in meters

APPENDIX H

RAW NAVIGATION DATA

Contained in this appendix is the raw navigation data obtained during the demonstration with the GPS prototype receiver. Included with the navigation data for a particular reference point is the time of the reading, the number of satellites available and general remarks regarding terrain, foliage and ephemeris uploads. This appendix lists all readings taken both prior to the daily emphemeris upload and after only three satellites were available. The survey data for the reference points to which these readings were compared is contained in Appendices E, F, and G.

TABLE 22

RAW NAVIGATION DATA - DAY 1

Date: 13 October 1980
Area: Nacimiento Valley(HL-17)
Spoke Test
Total Time: 109 min

Ref. Pt	Northing	Easting	Altitude	Time	No. Sate.	Remarks
A	82 089	51 175	372	19 34 34	5	open
B	82 154	51 153	387	19 50 20	5	open
	82 140	51 155	391	19 57 02	5	
C	82 126	51 200	401	20 08 14	5	open
D	82 094	51 207	392	20 12 22	5	open
E	82 047	51 201	401	20 33 20	5	oak
	82 050	51 187	397	20 43 10	5	canopy
F	82 040	51 155	401	20 52 50	5	open
G	82 054	51 142	400	20 48 02	5	open
H	82 057	51 109	404	20 57 50	5	oak canopy
I	82 161	51 185	392	22 03 08	3	open
J	82 197	51 226	392	22 11 30	3	open
K	82 183	51 161	394	22 00 22	5	open
L	82 158	51 220	413	20 05 08	5	open
M	82 089	51 257	394	20 15 48	5	open
N	82 011	51 226	398	20 29 06	5	partial canopy
O	81 999	51 152	404	21 04 52	5	open
P	82 011	51 142	395	21 01 26	5	open
Q	82 006	51 067	329	21 29 12	4	oak canopy
R	82 135	51 096	392	21 53 12	3	open
S	82 214	51 139	392	21 57 56	3	open
T	82 089	51 301	407	20 19 56	5	open
U	81 926	51 166	392	21 13 10	5	open
V	81 947	51 159	404	12 09 10	5	oak canopy

Ref. Pt	Northing	Easting	Altitude	Time	No. Sate	Remarks
W	81 907	51 136	401	21 18 14	5	oak canopy
X	82 099	51 324	409	20 23 14	5	oak canopy
Y	81 880	51 153	394	21 23 00	5	oak canopy

TABLE 23

RAW NAVIGATION DATA - DAY 2

Date: 14 October 1980
Area: Upper Milpitas Area
Total Time: 101 min

Ref. Pt	Northing	Easting	Altitude	Time	No. of Sate	Remarks
BM 198-14	91 497	55 531	1099	20 01 04	4	
M77	92 129	55 212	690	20 08 42	4	
RM1	92 087	55 298	625	20 12 10	4	
RM2	92 135	55 332	669	20 15 02	4	
M76	92 956	55 409	598	20 21 18	4	NAVSTAR #2
M75	93 382	55 343	620	20 51 24	4	Deleted
RM1	93 378	55 331	620	20 52 30	4	
RM2	93 368	55 347	627	20 54 46	4	
M74	93 597	55 397	606	20 46 46	4	All Points Exposed and Unobstructed
RM1	93 605	55 385	621	20 47 34	4	
RM2	93 596	55 387	611	20 48 56	4	
M75	93 382	55 343	620	20 51 24	4	
RM1	93 378	55 331	620	20 52 30	4	
RM2	93 368	55 347	627	20 54 46	4	
M73						
RM1	93 860	55 758	578	21 00 10	4	
RM2	93 862	55 727	586	21 01 58	4	
M74	93 605	55 373	611	21 06 46	4	
RM1	93 612	55 378	614	21 08 38	4	
RM2	93 594	55 375	613	21 10 58	4	
M75	93 382	55 348	631	21 13 28	4	
RM1	93 383	55 328	631	21 14 58	4	
RM2	93 370	55 354	636	21 16 24	4	
M76	93 009	55 354	604	21 21 00	4	
M77	92 165	55 282	728	21 28 38	4	
RM1	92 162	55 274	733	21 31 42	4	
RM2	92 188	55 293	735	21 30 28	4	
BM 198-14	91 433	55 578	733	21 40 28	3	
HL-8	91 455	55 575	737	21 42 08	3	
M75	93 147	55 348	669	20 29 24	4	Ephemeris update
RM1	93 525	55 340	848	20 32 50	4	
RM2	93 569	55 434	954	20 34 58	4	

TABLE 24

RAW NAVIGATION DATA - DAY 3

Date: 15 October 1980
Area: Upper Milpitas Valley
Total Time: 102 min

Ref. Pt	Northing	Easting	Altitude	Time	No. Sate	Remarks
M62	93 891	52 930	468	19 55 06	4	Medium Vegetation and Foliage Coverage
HL38	92 631	53 081	637	20 09 06	4	
HL39	92 146	54 096	621	20 22 10	4	
M63						
RM1	93 206	53 385	633	20 34 56	4	
RM2	93 202	53 415	616	20 33 22	4	
M64	93 309	53 762	695	20 41 54	4	
RM1	93 386	53 762	677	20 44 14	4	
M65	93 504	53 851	700	20 48 18	4	
RM2	93 499	53 844	992	20 49 52	4	
M66	93 749	53 857	991	20 54 32	4	
RM2	93 747	53 880	983	20 56 28	4	
M67	94 077	54 014	968	21 11 56	4	
RM1	94 099	54 005	991	21 13 10	4	
RM2	94 061	54 011	954	21 09 38	4	
M68	94 198	53 890	1027	21 01 08	4	
RM1	94 210	53 893	1023	21 03 16	4	
RM2	94 192	53 924	1027	21 04 44	4	
HL37	91 465	53 043	347	21 30 46	3	
HL36	89 839	53 773	338	21 37 56	3	

* No ionospheric delay correction due to broken L2 antenna connector

TABLE 25

RAW NAVIGATION DATA - DAY 4

Date: 16 October 1980
Area: Nacimiento Valley
Total Time: 96 min

Ref. Pt	Northing	Easting	Altitude	Time	No. Sate	Remarks
E11	79 632	53 953	171	18 36 50	4	Ephemeris
HL21	78 700	55 573	175	18 45 58	4	Upload
HL18	81 937	51 595	399	19 01 16	3	in
HL17	82 114	51 201	399	19 04 39	3	Progress
HL22	80 749	54 426	382	19 54 24	4	open
HL22 Offset	80 740	54 373	423	19 57 46	4	trees
HL20	79 716	54 065	394	20 01 52	4	open
HL21	78 512	55 420	396	20 09 52	4	open
HL22 Offset	80 743	54 370	392	20 17 50	4	trees
HL22	80 758	54 417	387	20 19 46	4	open
HL18	81 905	51 563	392	20 25 48	4	open
HL17	82 087	51 162	399	20 29 52	4	open
HL18	81 907	51 560	397	20 36 08	4	open
HL22	80 758	54 409	394	20 41 46	4	open
HL22 Offset	80 738	54 356	394	21 30 04	3	trees
HL20	73 713	54 056	391	21 33 38	3	open
HL22	80 833	54 476	401	21 55 00	3	open

TABLE 26

RAW NAVIGATION DATA - DAY 5

Date: 17 October 1980
Area: Nacimiento Valley
Static Test
Total Time: 16 min

Ref. Pt	Northing	Easting	Altitude	Time	No. Sate	Remarks
HL21	78 519	55 411	421	20 56 52	4	Unobstructed
HL21	78 515	55 417	423	20 57 54	4	
HL21	78 513	55 411	419	20 58 16	4	
HL21	78 514	55 412	412	20 59 12	4	
HL21	78 513	55 401	416	21 00 00	4	
HL21	78 522	55 408	419	21 01 08	4	
HL21	78 526	55 407	422	21 01 50	4	
HL21	78 520	55 412	421	21 02 32	4	
HL21	78 518	55 408	427	21 03 14	4	
HL21	78 514	55 414	423	21 04 07	4	
HL21	78 522	55 407	426	21 04 02	4	
HL21	78 522	55 413	421	21 05 24	4	
HL21	78 518	55 417	423	21 06 06	4	
HL21	78 521	55 416	414	21 06 48	4	
HL21	78 521	55 413	426	21 07 30	4	
HL21	78 520	55 411	421	21 08 14	4	
HL21	78 522	55 409	419	21 08 56	4	
HL21	78 523	55 405	425	21 09 38	4	
HL21	78 526	55 411	426	21 10 20	4	
HL21	78 532	55 417	425	21 11 22	4	
HL21	78 526	55 407	430	21 11 44	4	
HL21	78 528	55 414	431	21 12 28	4	
HL22	80 756	54 410	408	19 54 02	4	
HL22 Offset	80 739	54 347	443	20 25 14	4	
HL22 Offset	80 738	54 342	414	20 26 56	4	

Ref. Pt	Northing	Easting	Altitude	Time	No. Sate	Remarks
HL22 Offset	80 739	54 347	421	20 27 52	4	
HL22 Offset	80 742	54 348	424	20 28 48	4	
HL22 Offset	80 747	54 350	438	20 29 34	4	Heavy Vegetation
HL22 Offset	80 744	54 348	434	20 30 54	4	
HL22 Offset	80 746	54 347	436	20 31 50	4	
HL22 Offset	80 747	54 347	423	20 32 46	4	
HL22 Offset	80 746	54 352	424	20 33 52	4	
HL22 Offset	80 746	54 350	425	20 34 50	4	
HL22 Offset	80 747	54 351	430	20 35 46	4	
HL22 Offset	80 747	54 348	429	29 36 54	4	
HL22 Offset	80 742	54 351	434	20 38 00	4	
HL22 Offset	80 747	54 358	440	20 38 56	4	
HL22 Offset	80 750	54 341	436	20 39 52	4	
HL20	79 725	54 050	427	20 46 36	4	
HL17	82 111	51 163	399	21 27 22	3	Altitude Hold Mode
HL17	82 113	51 164	403	21 28 30	3	
HL17	82 104	51 162	401	21 29 12	3	
HL17	82 095	51 155	401	21 29 54	3	
HL17	82 089	51 145	401	21 30 36	3	
HL17	82 104	51 160	398	21 31 18	3	
HL17	82 129	51 180	---	21 32 00	--	
HL17	82 120	51 171	401	21 32 58	3	

Ref. Pt	Northing	Easting	Altitude	Time	No. Sate	Remarks
Date: 17 October 1980						
Area: Nacimiento Valley						
Total Time: 5 min						
HL18	81 943	51 586	401	21 35 40	3	Altitude Hold Mode
HL18	82 934	51 573	402	21 36 32	3	
HL18	81 940	51 579	401	21 37 00	3	
HL18	81 921	51 557	401	21 37 46	3	
HL18	81 938	51 569	401	21 38 28	3	
HL18	81 919	51 560	403	21 39 10	3	
HL18	81 937	51 575	398	21 39 52	3	
HL18	81 934	51 562	401	21 40 34	3	
Date: 17 October 1980						
Area: Nacimiento Valley						
Total Time: 4½ min						
HL22	80 807	54 454	396	21 46 48	3	Altitude Hold Mode
HL22	80 821	54 466	398	21 47 10	3	
HL22	80 814	54 442	399	21 47 52	3	
HL22	80 832	54 472	397	21 48 34	3	
HL22	80 800	54 438	399	21 49 16	3	
HL22	80 808	54 451	398	21 49 58	3	
HL22	80 826	54 468	398	21 50 40	3	
HL22	80 835	54 485	398	21 51 22	3	

LIST OF REFERENCES

1. Instrumentation Command Player Instrumentation Capabilities, CDEC, BDM Services Company, 25 February 1980, p. 26.

2. Instrumentation Required Operational Capabilities (IROC), CDEC, February 1980, p. III-5.

3. Capabilities of the CDEC Multi-Computer System, CDEC, BDM Services Company, 28 September 1979, p. II-4.

4. Range Measurement System/Simulated Combat Operations Range Equipment (RMS/SCORE), General Dynamics-Electronics Division, June 1977, p. 2-4.

5. Simulated Combat Operations Range Equipment (SCORE), Dynamics Electronics Division, May 1976, p. A-2.

6. Weaver, Dr. Wm. B., Position Location Accuracy Analysis: Dynamic Responses of FHL PL Systems, BDM Services Company, p. 10.

7. Ibid., p. 10.

8. Weaver, Dr. Wm. B., Memorandum-Subject: Position Location Accuracy: Polling and Geometry, BDM Services Company, 6 December 1977, p. 1.

9. Weaver, Dr. Wm. B., Position Location Accuracy Analysis: Dynamic Responses of FHL PL Systems, BDM Services Company, pp. 12-14.

10. Simulated Combat Operations Range Equipment (SCORE), General Dynamics Electronics Division, May 1976, p. A-7.

11. Capabilities of the CDEC Multi-Computer System, CDEC, BDM Services Company, 28 September 1979, p. VI-20.

12. Simulated Combat Operations Range Equipment (SCORE), General Dynamics Electronics Division, May 1976, p. A-3.

13. Instrumentation Command Player Instrumentation Capabilities, CDEC, BDM Services Company, 25 February 1980, p. 50.

14. Capabilities of the CDEC Multi-Computer System, CDEC, BDM Services Company, 28 September 1979, p. I-7.

15. RMS Evaluation Final Report, BDM Services Company, February-March 1975 (Revised 13 June 1975), p. 18.

16. Final Report RMS/SCORE Accuracy Test, Air Force Test and Evaluation Center, Kirtland Air Force Base, New Mexico, March 1978, p. 38.

17. Weaver, Dr. Wm. B., Range Measuring System Accuracy Study, BDM Services Company, p. 19.

18. RMS Evaluation Final Report, BDM Services Company, February-March 1975 (Revised 13 June 1975), p. C-2.

19. Weaver, Dr. Wm. B., Position Location Accuracy Analysis: Dynamic Responses of FHL PL Systems, BDM Services Company, Appendix 6.

20. Ibid., Appendix 6.

21. Capabilities of the CDEC Multi-Computer System, CDEC, BDM Services Company, 28 September 1979, p. II-3.

22. Weaver, Dr. Wm. B., Range Measuring System Accuracy Study, BDM Services Company, p. 15.

23. Capabilities of the CDEC Multi-Computer System, CDEC, BDM Services Company, 28 September 1979, p. II-4.

24. Watkins, Warren Seki, Command and Control Functions and Organizational Structure Required to Support the NAVSTAR/Global Positioning System (Thesis-Naval Postgraduate School), June 1980, p. 76.

25. Ibid., p. 84.

26. Russell, S.S. and Schaibly, J.H., "Control Segment and User Performance", NAVIGATION: Journal of the Institute of Navigation, Vol. 25, No. 2, Summer 1978, p. 167.

27. Spilker, James J., Jr., "GPS Signal Structure and Performance Characteristics", NAVIGATION: Journal of the Institute of Navigation, Vol. 25, No. 2, Summer 1978, p. 128.

28. Ibid., p. 130.

29. Ibid., p. 140.

30. Ibid., p. 140.

31. Ibid., p. 144.

32. Kruczynski, L.R., "Aircraft Navigation with Limited Operational Phase of the NAVSTAR/Global Positioning System", NAVIGATION: Journal of the Institute of Navigation, Vol. 24, No. 4, Winter 1977-78, p. 248.

33. Phase I NAVSTAR/GPS Major Field Test Objective Report Tropospheric Correction, NAVSTAR/GPS Joint Program Office, SAMSO, 4 May 1979 (draft), p. 2.

34. Major Field Test Objective Report on Navigation Accuracy: Position Accuracy, General Dynamics-Electronics Division, 25 June 1979, pp. 2-4.

BIBLIOGRAPHY

Bartholomew, C.A., "Satellite Frequency Standards", NAVIGATION: Journal of the Institute of Navigation, Vol. 25, No. 2, Summer 1978.

Birnbaum, M. et.al., "The GPS Navigation Message", NAVIGATION: Journal of the Institute of Navigation, Vol. 25, No. 2, Summer 1978.

Carrier, L., Rosen, E., and Van Leevwen, A., "The Global Positioning System and Its Application in Spacecraft Navigation", NAVIGATION: Journal of the Institute of Navigation, Vol. 26, No. 2, Summer 1979.

Coriat, H. and Henderson, D.W., "Status Report-Global Position System", NAVIGATION: Journal of the Institute of Navigation, Vol 27, No. 1, Spring 1980.

Final Users Field Test Report for the NAVSTAR/GPS Phase I Major Field Test Objective Report on Environment Effects: Multipath, General Dynamics-Electronics Division, 15 June 1979.

Final User Field Test Report for the NAVSTAR/GPS Phase I Major Field Test Objective Report on Navigation Accuracy: Effects of Dynamics on Navigation Accuracy, General Dynamics-Electronics Division, 25 June 1979.

Glazer, B.G., "GPS Receiver Operation", NAVIGATION: Journal of the Institute of Navigation, Vol. 25, No. 2, Summer 1978.

Global Positioning System (GPS) Manpack/Vehicular User Equipment (MVUE) Set Description, Vol. II, Texas Instruments Incorporated-Equipment Group, 15 August 1979.

Instrumentation Master Plan, CDEC, 1980.

Major Field Test Objective Report on Demonstration of Military Value, Static Position, NAVSTAR/Global Positioning System, Joint Program Office, SAMSO, 7 May 1979.

Major Field Test Objective Report on Environmental Effects Foliage Attentuation, NAVSTAR/Global Positioning System, Joint Program Office, SAMSO, 7 May 1979.

Major Field Test Objective on GPS Velocity Accuracy, NAVSTAR/GPS, Joint Program Office, SAMSO, 30 May 1979.

Major Field Test Objective Report on System Characteristics, Signal Level and Signal Structure, NAVSTAR/GPS Joint Program Office, SAMSO, 30 May 1979.

Martin, E.H., "GPS User Equipment Error Models", NAVIGATION: Journal of the Institute of Navigation.

RMS/SCORE, Executive Summary, A Position/Location System for Modern Military Weapons Testing, Training and Tactics Evaluation, General Dynamics-Electronics Division, July 1980.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93940	2
3.	Department Chairman, Code 62 Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	1
4.	Professor Glen A. Myers, Code 62Mv Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	2
5.	Professor John E. Ohlson, Code 62Ol Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	2
6.	Captain William L. Reinhart CCEIA-Europe (W3H8AA A) APO, New York 09056	1
7.	Commander ATTN: ATEC-IC U.S. Army Combat Developments Experimentation Command Fort Ord, California 93941	1
8.	Commander ATTN: ATEC-SA U.S. Army Combat Developments Experimentation Command Fort Ord, California 93941	1
9.	Commander ATTN: ATEC-PL U.S. Army Combat Developments Experimentation Command Fort Ord, California 93941	1

10. Commander 1
ATTN: ATEC-IC-E
U.S. Army Combat Developments Experimentation Command
Fort Ord, California 93941

11. Commander A. Durkee 1
ATTN: SD/YE-DOT
Post Office Box 93960
World Way Postal Center
Los Angeles, California 90009

12. Lieutenant Colonel E. Harvey 1
ATTN: SD/TACLO
Post Office Box 92960
World Way Postal Center
Los Angeles, California 90009

13. Commander Day 1
ATTN: SD/YET
Post Office Box 92960
World Way Postal Center
Los Angeles, California 90009

14. Colonel Goldtrap 1
ATTN: SD/YEA
Post Office Box 92960
World Way Postal Center
Los Angeles, California 90009

Thesis
R32985 Reinhart 193291
c.1
Application of the NAVSTAR/GLOBAL positioning system on instrumented ranges.